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Coal Gasification Processes for Retrofitting Military Central Heating Plants: Overview

by
Robert Sheng
Rene Laurens
Christopher F. Blazek
Gary W. Schanche

Federal legislation has mandated that Department of Defense (DOD) installations double their coal consumption in an effort to lower fuel costs at central heating plants. Most plants now use natural gas as fuel, which can cost two to three times as much per British thermal units (Btu) as current coal supplies. However, gas-fired boilers normally cannot be modified to burn coal directly; widespread replacement of the gas-burning equipment would be prohibitively expensive.

Coal gasification is a technology that could potentially resolve this problem. Coal gasifier equipment is available in a wide variety of capacities that could be retrofitted to gas-fired boilers. To help installations select optimal processes and equipment, this report reviews: coal gasification fundamentals, and equipment, plant demonstration programs, and industrial boiler conversions to use low-Btu gas from a coal gasification process.

It is recommended that coal gasification technology be considered wherever a coal-based heating plant is required. The gasifier technologies are reliable and are potentially cost-competitive with new coal-fueled plants and natural gas-fired plants.

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FOREWORD

This study was conducted for the U. S. Army Engineering and Housing Support Center (USAEHSC) under Project 4A162781AT45, "Energy and Energy Conservation"; Work Unit DO-006, "Coal Use Technologies." The USAEHSC Technical Monitor was B. Wasserman, CEHSC-FU.

This research was performed by the Energy and Utility Systems Division (FE), Infrastructure Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL). Dr. David M. Joncich is Chief, CECER-FE and Dr. Michael J. O'Connor is Chief, CECER-FL. Robert Sheng, Rene Laurens, and Christopher Blazek are with the Institute of Gas Technology.

COL Daniel Waldo, Jr., is Commander and Director of USACERL, and Dr. L.R. Shaffer is Technical Director.

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1 INTRODUCTION

Background

Congress has directed U. S. Department of Defense (DOD) installations to increase the amount of coal used in military commercial and industrial heating.[1] This action, intended primarily to lower DOD's heating plant operating costs, will have the additional benefit of boosting the domestic coal industry. The goal is to double coal consumption by 1994, with roughly 1.4 million short tons consumed in 1985 as a baseline.

Coal was burned extensively in the United States until the post-World War II era when natural gas became a plentiful, low cost, cleaner burning alternative. However, since the energy crisis in the 1970s and subsequent changes in pricing, natural gas is no longer the least-cost option at many installations. In fact, gas can cost two to three times more than coal on a per-Btu basis.

In attempting to use more coal to replace natural gas, DOD faces a problem: furnaces designed to run on gas cannot be modified to burn coal directly. However, large-scale replacement of these plants with coal-burning equipment would bear a prohibitive cost. Because of this situation, coal gasification has resurfaced as a promising technology for retrofitting gas plants to burn coal by first converting the coal to gases.

The method of producing low-Btu (<200 Btu/standard cubic foot [SCF])* and medium-Btu (200 to 400 Btu/SCF) gases from coal was used extensively through the mid-1940s until most heating applications switched to gas. Coal gasification received considerable attention during the energy crisis, but faded again as the natural gas supply became adequate in the early 1980s. This techology now represents a potentially lower cost alternative to replacing gas boilers at DOD installations. Due to the large cost differential between coal and gas, a retrofit costing as much as $10 million would pay for itself over the plant life cycle.

Coal gasification equipment is commercially available in the relatively small size range and fixed-bed configuration needed to retrofit most DOD boiler plants. To determine the feasibility of using this technology at military installations, information is needed on the coal gasification process, available equipment and technologies, feedstock requirements, operation and maintenance (O&M) considerations, and economics.

Objective

The objective of this work is to evaluate small-scale commercially available low- and medium-Btu coal gasification processes for potential use in retrofitting DOD gas-fired heating plants.

[1] Public Law (PL) 99-190, Defense Appropriations Act (1986); revised annually.
* A metric conversion chart appears on p 104.

Approach

State-of-the-art coal gasification processes and equipment were identified and evaluated for applicability to DOD facilities. This information was collected through a literature survey and interviews with industry representatives. Findings were compiled in the form of a review covering: coal gasification fundamentals, coal gasification equipment, recent demonstration programs for low-Btu gas coal gasification plants, industrial boiler convertibility, and interchangeability of low-Btu gas from the coal gasification process, with conventional natural gas and light oil.

Scope

This report is limited to processes and equipment producing low- and medium-Btu gases from coal since this capacity range is most suitable for typical DOD plants. In addition, the review covers these processes for all forms of coal that might be used (anthracite, bituminous, subbituminous, and lignite).

Mode of Technology Transfer

It is recommended that the information in this report be transferred as an Engineer Technical Note (ETN) to provide advance notification to the field. Depending on the success of this technology in meeting DOD's increased coal consumption goals, this information may be used to update the appropriate criteria documents.

2 COAL GASIFICATION FUNDAMENTALS

Coal gasification is the conversion of coal to combustible gases. Gases manufactured from coal are usually classified by their heating value. High-Btu gas consists essentially of methane, has a heating value (HHV) of approximately 1000 Btu/SCF, and is interchangeable with natural gas. Medium-Btu gas consists primarily of carbon monoxide, hydrogen, and small amounts of carbon dioxide with heating values in the range of 250 to 600 Btu/SCF. Medium-Btu gas can be used as an industrial fuel or as a raw material for chemical synthesis. Low-Btu gas has a higher heating value between 100 and 200 Btu/SCF. It is used mainly as an industrial fuel gas. Table 1 summarizes compositions and heating values of some typical manufactured gases.

Coal Gasification Chemistry

Coal is an extremely complex solid substance for which the chemical composition is mostly carbon (C) with relatively lesser amounts of hydrogen (H), oxygen (O), nitrogen (N), sulfur (S), and ash. Coal gasification is the conversion of coal matter to combustible gases. Some of the important reactions in coal gasification are listed in Table 2. These reactions can occur individually or, in most cases, in combinations.

Raw coal fed to the gasifier comes into contact with the hot raw gases, and moisture in the coal is driven off. As coal heats up, occluded carbon dioxide and methane are driven off at temperatures less than 400 °F. Organic sulfur in the coal decomposes and is converted to hydrogen sulfide in the range of 400 to 900 °F. Nitrogen compounds in the coal decompose, releasing nitrogen and ammonia. Above 550 °F, oils and tars are distilled from the coal. The devolatilized coal, or char, reacts with the steam feed and combustion products such as carbon dioxide to form carbon monoxide and hydrogen. The heat required for the endothermic steam-carbon and carbon dioxide-carbon reactions is provided by the exothermic combustion reaction of the remaining carbon in the char with the oxygen feed.

All coal gasification processes are essentially controlled by balancing the heat effects of the exothermic and endothermic reactions, and require an input of heat at high temperatures. Basically, this heat can be provided by: (1) combustion of carbon with the oxygen contained in air, (2) combustion of carbon with oxygen separated from air, and (3) the use of an indirect heat carrier.

The direct use of air for combustion of carbon as a heat input results in the production of low-Btu gas because the product gas is diluted with air nitrogen. Medium-Btu gas generally requires an air separation plant to provide relatively pure oxygen as the reactant gas. The medium-Btu gas can then be further upgraded by additional processing steps, such as methanation, to high-Btu gas. Most of the earlier work in coal gasification process development was influenced by the desire to eliminate the expensive air separation plant. Improvements in oxygen production have reduced this incentive, so that most modern processes for medium- and high-Btu gas are now directly fired with oxygen using steam for temperature control and internal hydrogen production.

Processes and Equipment

The many coal gasification processes available are characterized to a large extent by the contacting method between the coal and reactant gases in the gasifier. The contacting method is determined primarily by the way in which coal moves through the gasifier vessel. The three mechanisms of movement, which also define the gasifier type are: (1) fixed-bed, (2) fluidized-bed, and (3) entrained-bed.

Table 1

Typical Manufactured Gas Composition

Component	Producer Gas: Bituminous Coal	Producer Gas: Anthracite	Producer Gas: Coke	Coke Oven Gas	Blue Water Gas	Carbureted Water Gas	Natural Pipeline Gas
CO	25.0	27.1	30.0	6.3	38.5	34.0	
H_2	14.5		9.3	46.5	50.5	40.5	
CH_4	3.1	0.9	0.7	32.1	1.0	10.2	92.6
ILL[a]				4.0		8.0	0.31[b]
CO_2	4.7	5.0	3.6	2.2	6.0	3.0	0.90
N_2	52.7	50.4	55.4	8.1	3.5	2.9	0.95
O_2				0.8		0.5	
H_2S					0.5		
C_2H_6							4.27
C_3H_8							0.97
GHV[c]	167	151	137	584	300	550	1051

[a] ILL = illuminates, ethylene and heavier, = C_2+.
[b] Natural gas, 0.31 percent is heavier than C_3H_8.
[c] GHV = gross heating value, Btu/SCF.

Table 2

Coal Gasification Reactions

Combustion	$C + O_2$	—>	CO_2 + 169,300 Btu
Steam Decomposition	$C + H_2O$	—>	$H_2 + CO$ - 56,500 Btu
Methane formation	$C + 2H_2$	—>	CH_4 + 32,200 Btu
Carbon dioxide decomposition	$C + CO_2$	—>	2CO - 74,200 Btu
Water-gas shift	$CO + H_2O$	—>	$CO_2 + H_2$ + 17,700 Btu
Methanation	$CO + 3H_2$	—>	$CH_4 + H_2O$ + 88,700 Btu

Fixed beds are, in reality, very slowly moving columns of coal, in which coal is fed at the top and ash is removed at the bottom of the reactor vessel. In a fluidized bed, the reactant gases have sufficient velocity to suspend the coal particles, which move about in random motion, and the bed behaves much like a violently boiling fluid. The reactor is completely back-mixed. By increasing the reactant flow rate and decreasing the coal particle size, the gases will entrain and carry the particles, thus forming an entrained bed. Each bed type has many unique properties what will determine its suitability for a particular application. At present, coal gasifier designs are available in a wide variety of sizes (gasifier diameters from 3-1/2 to 18 ft with coal consumption capacities from 2.6 to 1000 ton/day) and product composition (gas heating values from 117 to 300+ Btu/SCF). The three types of gasifiers are described in more detail below.

Fixed-Bed Gasifier

In a "dry-ash" fixed-bed gasifier (Figure 1), as raw coal descends, it is dried and devolatilized using the sensible heat of the ascending gases. The devolatilized coal is then gasified in the gasification zone, and finally burned to ash in the combustion zone. The solids-gas reactions occur countercurrently. Figure 2 shows a typical temperature profile for the coal in various gasifier reaction zones. The zones are not distinct as shown but blend gradually into each other. In the drying zone, the raw coal is heated and dried by direct contact with the ascending gases. When the temperature of coal rises above 550 °F in the devolatilization zone, the volatile matter consisting of oils, tars, and gases starts to evolve. This zone is followed by the gasification zone where the char (fixed carbon) gasifies by reaction with steam and combustion product gases coming from the combustion zone directly below. In the combustion zone, the remaining char burns and reacts with the feed gases to provide the heat and gases for the gasification reactions. Finally, the ash is cooled by reactant gases in the ash zone prior to discharge.

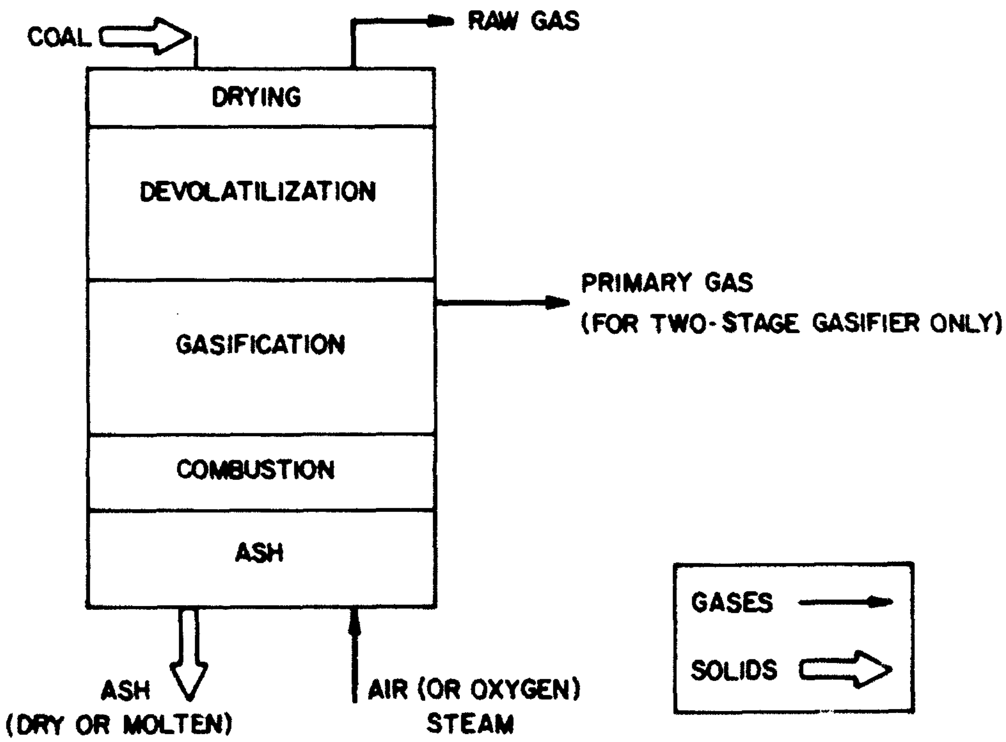

Figure 1. Fixed-bed gasifier.

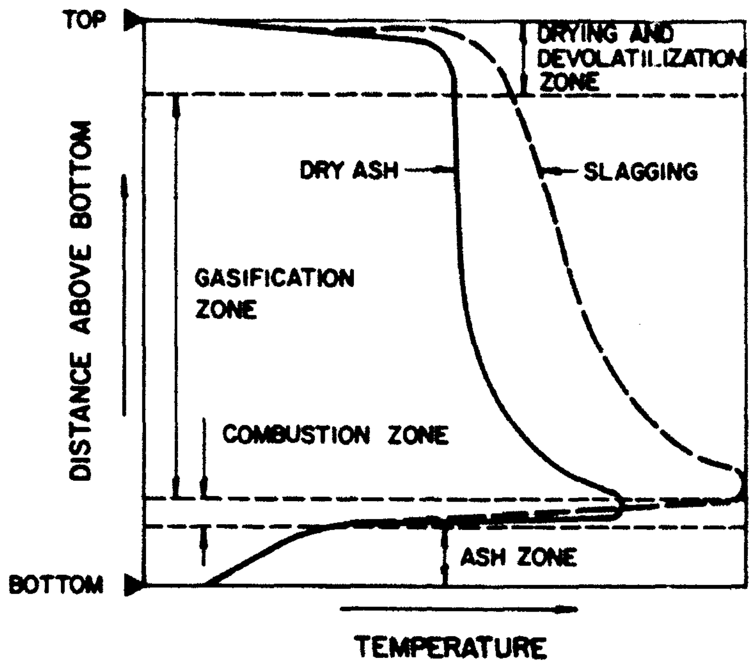

Figure 2. Typical temperature profile of coal in a fixed-bed gasifier.

Dry-ash fixed-bed gasifiers can be further classified as single- and two-stage units. Both types contain the zones described above; they differ in the location of product gas removal and the temperature ranges within the devolatilization and drying zones. A single-stage gasifier has only one product gas offtake located at the top of the drying zone. Temperatures of gas leaving this type of unit are in the range of 700 to 1100 °F. Thus, incoming coal is heated very rapidly and causes the oils and tars evolved from the coal to crack and polymerize to heavy, viscous tar and pitch. This violent distillation also causes the coal to decrepitate and gives rise to coal dust, which is carried out with the product gas.

Two-stage gasifiers have one gas offtake located above the drying zone and another just at the top of the gasification zone. Most of the raw gases are removed at the top of the gasification zone; the remaining gases flow upward through the devolatilization and drying zones. The temperatures attained in these two zones are considerably lower than those seen in single-stage units. Therefore, the incoming coal is heated, and the oils and tars are evolved much more slowly. The gentle devolatilization produces a tar of lower viscosity in the form of fine mists. This tar can be removed from the gas stream by a hot-stage electrostatic precipitator. The raw gas cleanup system is therefore greatly simplified compared with single-stage units.

In a "slagging-ash" fixed-bed gasifier, the temperature in the combustion zone is maintained several hundred degrees above the ash fusion temperature, at which ash melts to a liquid slag. The steam feed rate to the gasifier is greatly reduced compared with "dry ash" fixed-bed gasifiers because no excess steam is required to control the combustion zone temperature below the ash-softening temperature. Slagging operation allows the gasifier to directly process highly caking, low reactivity coals such as bituminous coal without requiring an internal mechanical agitator. Raising the gasifier temperature converts more of the available carbon to combustible gas product and produces a smaller amount of tar/oil byproduct. The slagging-ash fixed-bed process has not been fully commercialized.

The countercurrent solids-gas contact in the fixed-bed unit results in high thermal efficiency. Solids carryover by the raw product gas is much less compared with the other types of gasifiers. The longer solids residence time also yields higher carbon conversion. However, a fixed-bed unit generally requires a coarse-sized coal feed between 1/4 and 1-1/2 in. Particles finer than 1/4 in. are not acceptable and must be handled separately because fines can cause gas maldistribution and short-circuiting in the gasifier. The tars and oils contained in the raw product gas, if excessive—especially for a single-stage unit—can cause additional downstream gas handling problems.

Fixed-bed gasifiers are available in the size range most appropriate for DOD boiler plant retrofit, assuming maximum facility coal usage of approximately 500 ton/day. This size unit would allow for multiple gasifier trains at the large base plants, which would also facilitate load following. In addition, single-train gasifier operations could supply gas to the relatively small military boiler plants.

Fluidized-Bed Gasifier

A stationary bed of coal particles (typically less than 3/8 in.) becomes fluidized when the velocity of the gasifying agents moving through the bed is sufficient to lift the coal particles (Figure 3). The bed expands and the coal particles move about randomly. This fluidized action causes thorough mixing of the coal and gases, and the bed exhibits almost isothermal conditions. Bed temperatures are in the 1500 to 1900 °F range, depending on coal type.

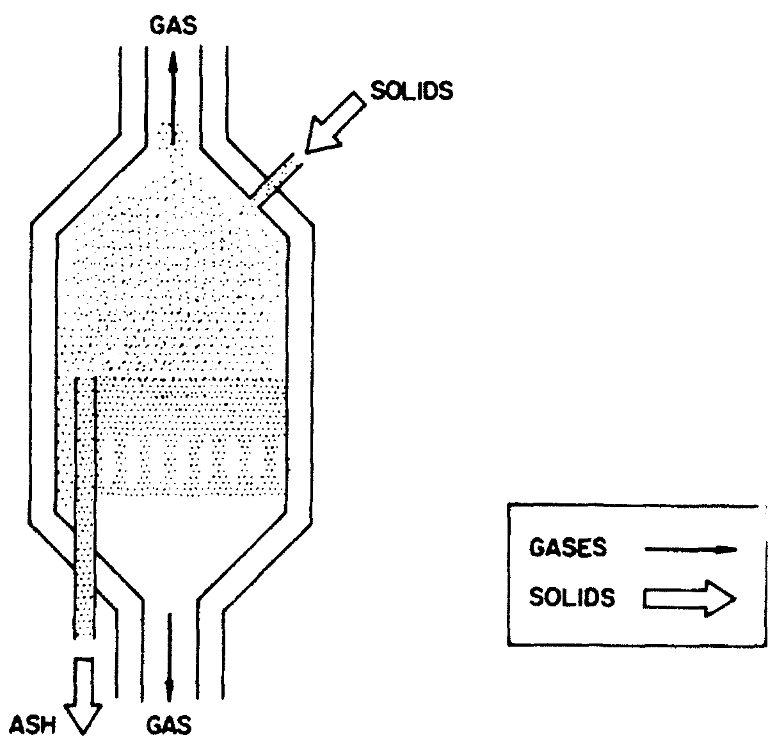

Figure 3. Fluidized-bed gasifier.

Because of these mixing properties, fluidized beds can handle a higher coal feed rate than fixed beds for the same size reactor. The temperature of the reactor exit gases is about the same as that of the bed. A heat exchange device is usually required to recover the heat contained in the product gases. Compared with fixed beds, fluidized beds have: (1) more solids carried over with the product gases, (2) less tar and oil production, and (3) more unreacted carbon in the ash.

Ideally, ash would be removed by the heavier ash particles working their way downward through the bed and falling out at the bottom. In the only commercially available fluidized-bed gasifier (Winkler), about 30 percent of the ash is removed in this way; the remaining 70 percent is carried out with the product gases.

The fluidized-bed gasifier generally cannot handle highly caking coals without an oxidative pretreatment step. The residue ash particles of caking coal agglomerate at high temperature to form large clinkers and can cause defluidization of the gasifier bed. The pretreatment process reduces the coal's caking tendency by partial oxidation of the coal particles' surface, but up to one-third of the volatile matter in the raw coal is also reacted in the process. Some fluidized-bed gasifiers that can directly gasify highly caking coals are in the advanced stage of development or near commercialization.

Entrained-Bed Gasifier

The entrained-bed gasifier (Figure 4) typically uses a pulverized coal feed of 70 percent passing through 200 mesh (U.S. Screen). The coal particles are conveyed pneumatically or entrained by the reactant gases. The velocity of the gas-solid mixture is usually about 20 ft/sec or higher, depending on the fineness of the coal. There is little or no mixing of the solids and gases, except when the gases initially contact the solids.

The entrained-bed gasifier operates at relatively high temperatures (2500 to 3000 °F) with extremely rapid conversion of the coal particles. Because of the high reaction temperatures, the oxygen consumption is usually higher and the steam consumption is usually lower than for other gasification systems. At such high temperatures, ash is melted and removed as a liquid slag. Caking coals can be fed directly to an entrained-bed gasifier without requiring need of oxygen pretreatment to reduce its caking tendency. The gasifier's operating conditions at high temperatures require special refractory lining to prevent slag corrosion and/or solids erosion. Limestone flux may be added to the coal to adjust the ash-fusion characteristics and the molten slag viscosity.

Effects of Coal Properties on Coal Gasification Systems

Moisture Content

The moisture content of coal varies widely among ranks. Generally, lower rank coals contain more moisture than high rank bituminous or anthracites. The increased coal moisture content raises the heat input required for vaporization and lowers the heating value of the product gas. In fixed-bed units, a high moisture content in the raw coal requires an increase in residence time for drying, and thus lowers the gasifier capacity and the gasification rate. Entrained-bed units are particularly sensitive to coal moisture content because moisture inhibits the overall gasification reactions that must take place rapidly in this type of gasifier. Drying of raw coal is usually required for fluidized- and entrained-bed gasifiers to remove the surface moisture prior to gasification.

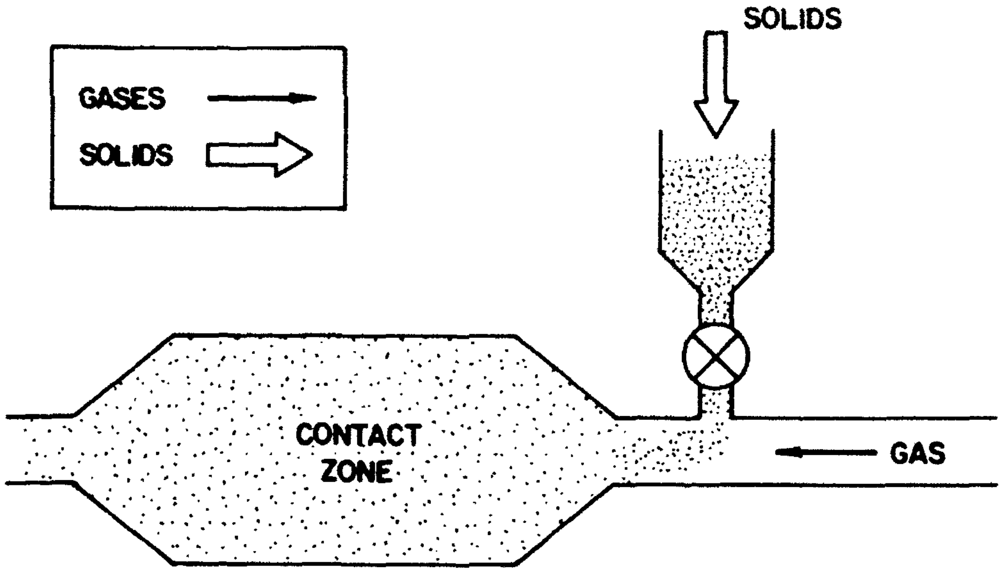

Figure 4. Entrained-bed gasifier.

Volatile Matter

Fluidized and entrained beds, compared with fixed beds, are less sensitive to the volatile matter content of the coal feed because these compounds are gasified very quickly. The solids residence time in the devolatilization zone of a fixed-bed gasifier is much longer, which causes low-molecular-weight gases, tars, and oils to evolve from the coal. Therefore, increases in the volatile matter content raise the heating value of the product gases. In single-stage fixed-bed units, some of the devolatilization products crack and polymerize to heavy tars and pitch, which must be removed from the product gas if the gas is not used directly. The effect of the volatile matter content on the composition of the product gases' major combustible components is shown in Figure 5.[2] The plotted curves are averaged values of more than 120 gasification tests with 59 different coals conducted in a Lurgi fixed-bed unit. For fixed-bed gasifiers, tar/oil production rises with increasing volatile matter content. The concentration of hydrogen and carbon monoxide in the product gas decreases with increasing volatile matter, while methane concentration remains relatively constant.

Fixed Carbon

Figures 6 through 9 show the effects of coal feed fixed carbon content on the heating value of the product gas and the gasification rate.[3] The product gas heating value decreases as the fixed carbon content increases from bituminous to anthracite coal. The gasification rate decreases with an increase in the coal feed's fixed carbon content.

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[2] P.F.H. Rudolph, "The Energy Process for Coal Gasification," *Energy Technology Handbook*, D.M. Considine (ED.) (McGraw-Hill, 1977).

[3] Gilbert/Commonwealth Co., *Fixed-Bed Coal Gasification for Production of Industrial Fuel Gas*, Report No. FE-2220-26 (U.S. Department of Energy [DOE], October 1977).

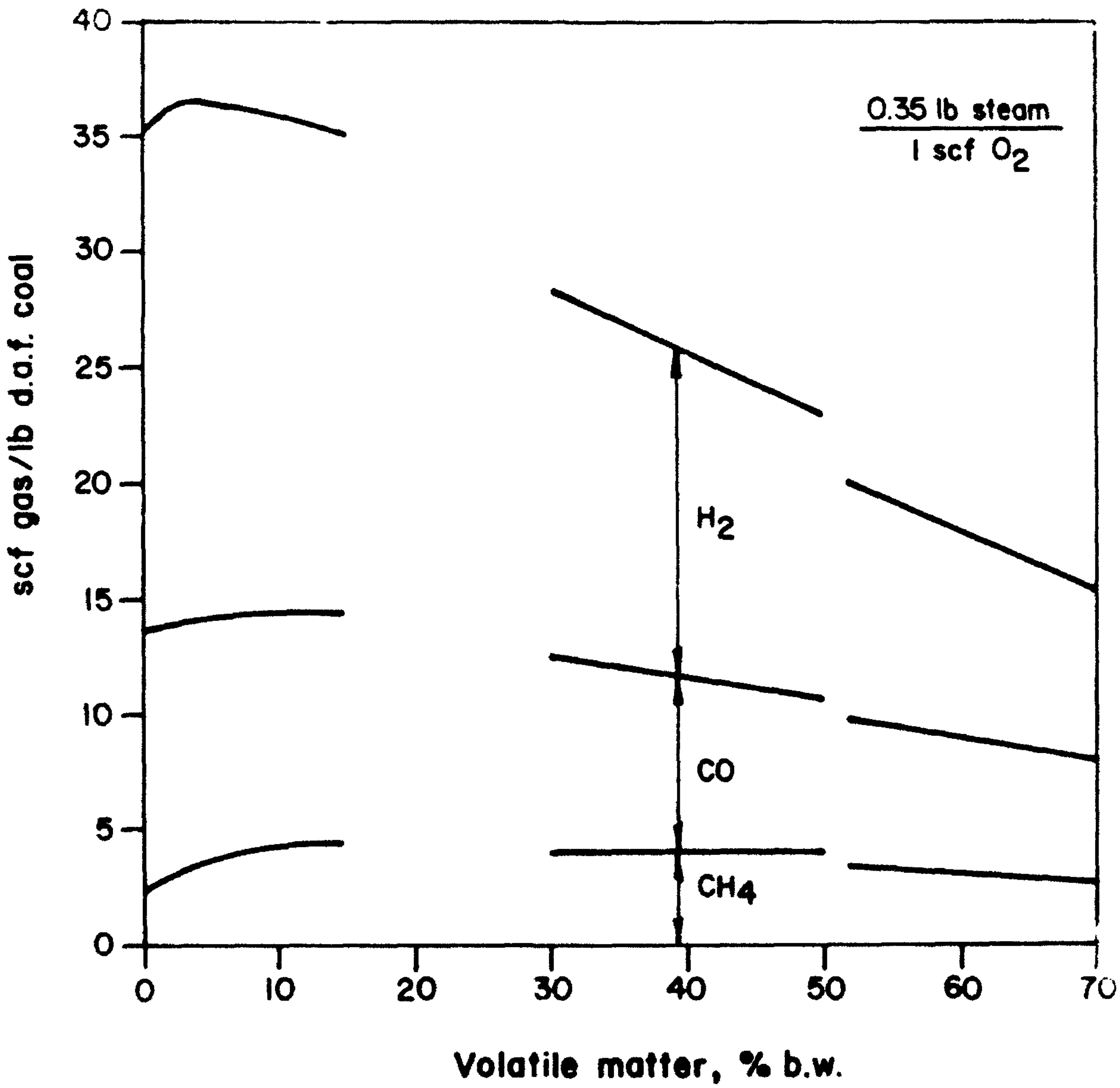

Figure 5. Gas production vs. coal grade (scf = standard cubic foot; d.a.f. = dry ash-free; b.w. = by weight).

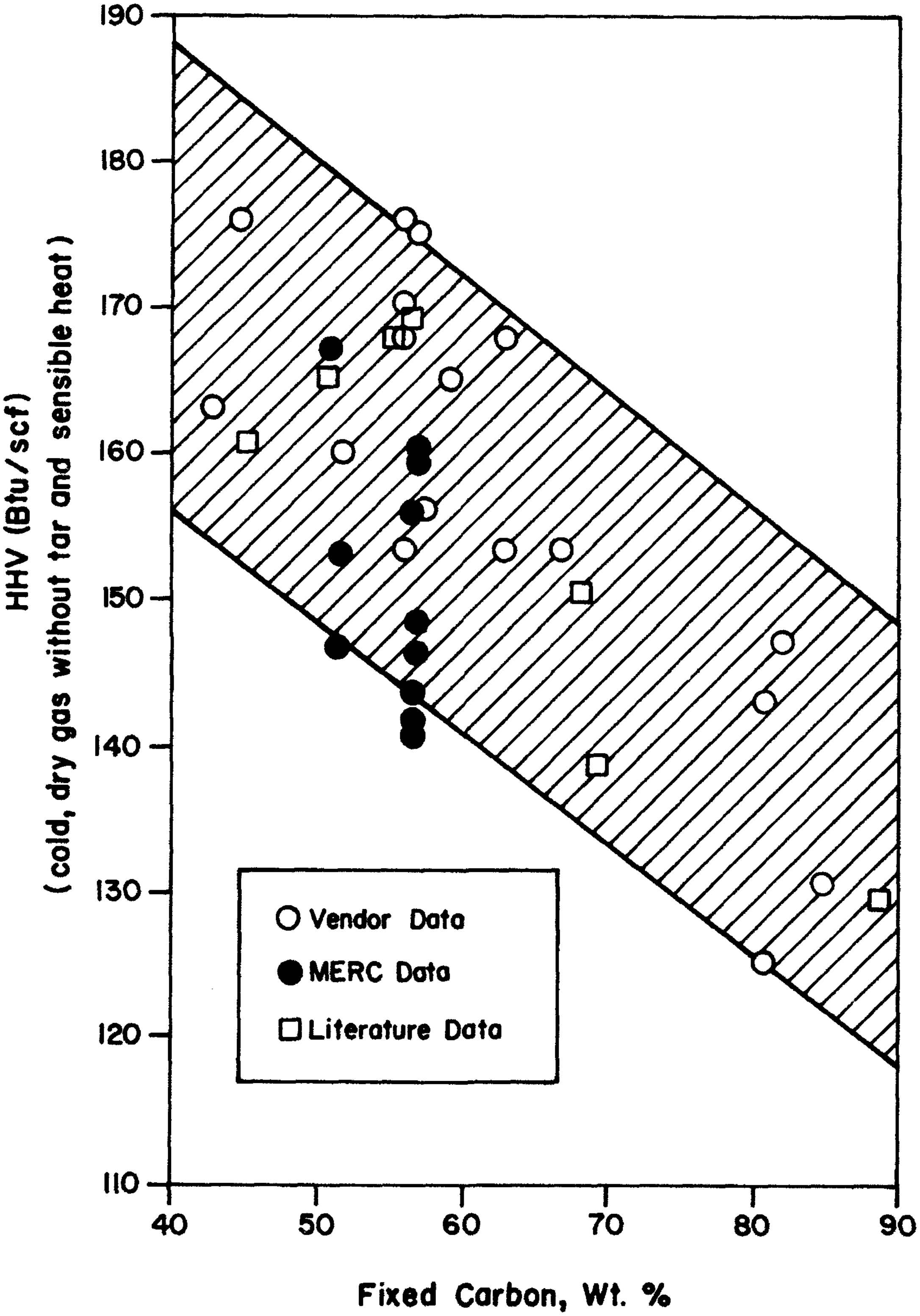

Figure 6. HHV of product gas vs. fixed carbon content of coal feed for air-blown, fixed-bed gasifier operating at atmospheric pressure.

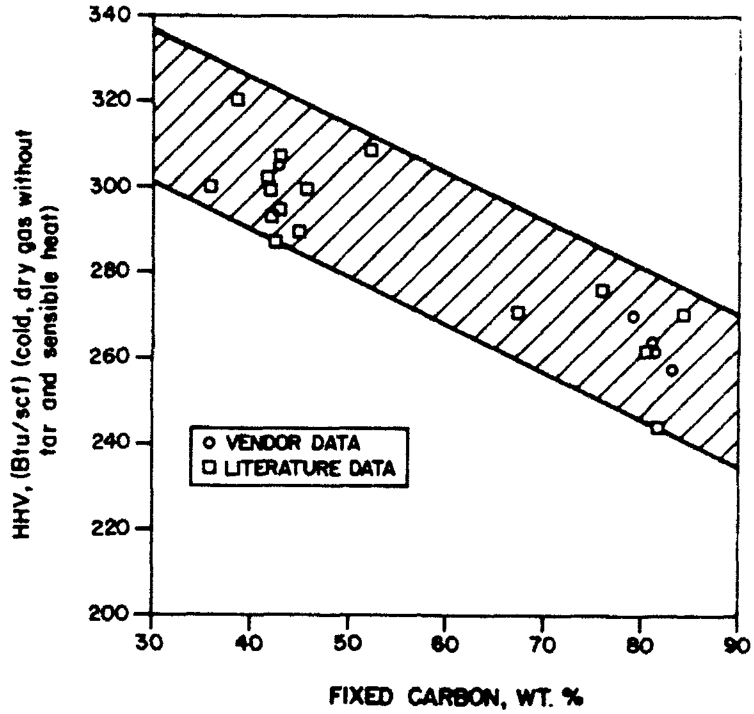

Figure 7. HHV of product gas vs. fixed carbon content of coal feed for oxygen-blown, fixed-bed gasifier operating at atmospheric pressure.

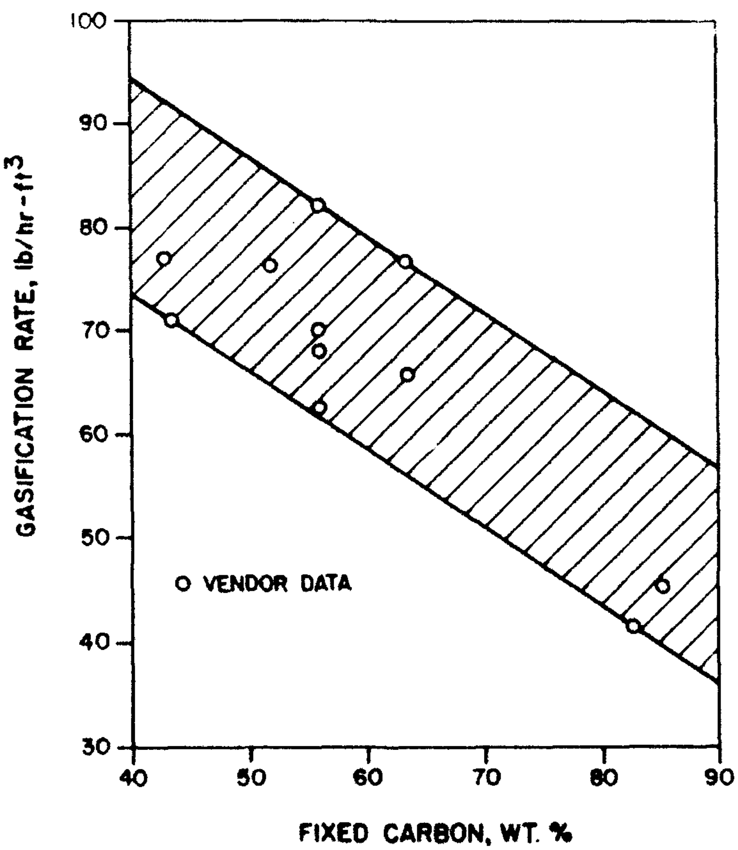

Figure 8. Gasification rate vs. fixed-carbon content of coal feed for air-blown, fixed-bed gasifier operating at atmospheric pressure.

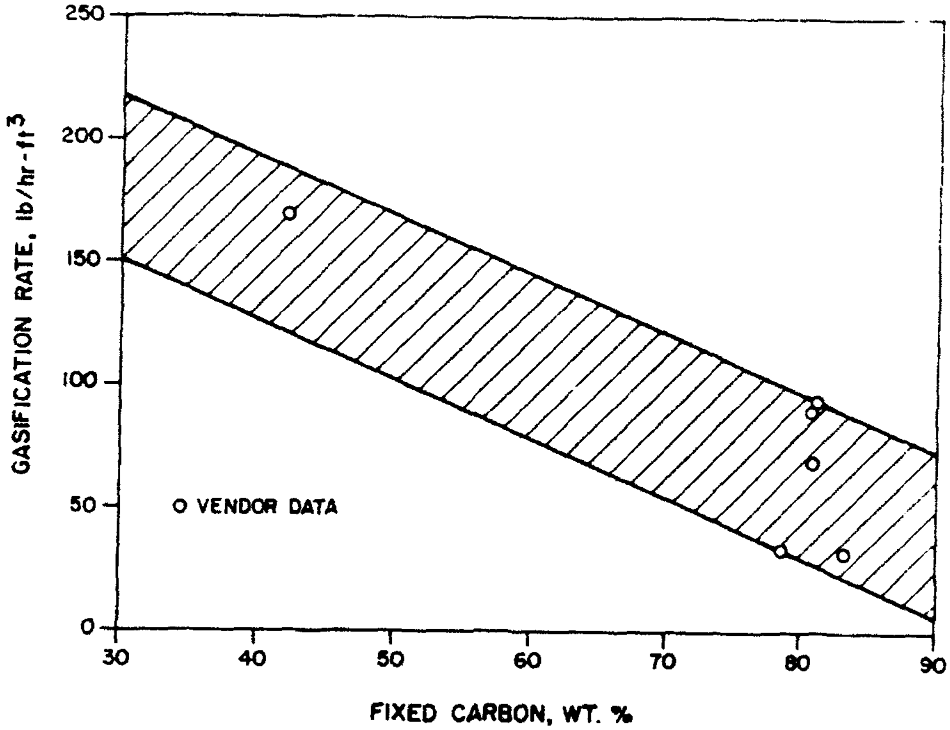

Figure 9. Gasification rate vs. fixed carbon content of coal feed for oxygen-blown, fixed-bed gasifier operating at atmospheric pressure.

Reactivity

As a general rule, the reactivity of coal increases with decreasing rank. For instance, anthracite coal has a much lower reactivity compared with lignite coal. The higher the reactivity, the lower the final reaction temperature at which the reactions approach equilibrium. The typical reaction temperatures of various coals are:

Coal Type	Final Reaction Temperature, °F
Lignite	1,200
Subbituminous	1,350
Semianthracite	1,450
Coke	1,500

The factors influencing reactivity are not well understood. It is generally believed that coal reactivity varies with volatile matter content, devolatilization rate, oxygen content, ash composition, and porous structure. For example, the high reactivities of lower rank coals are largely due to their high sodium and calcium contents. Coals with high reactivity can be gasified at lower temperatures and more coal is gasified per unit volume of gasification agents, i.e., oxygen/air and steam. Lower final reaction temperature means less heat is required in the process to maintain the reaction, and thus the increase in overall thermal efficiency compared with coal having a higher final reaction temperature.

Ash Content

Ash is the inorganic material remaining after coal is completely combusted. At high temperatures, the ash will melt and clinkers may form. The ash composition determines the temperature at which melting occurs. In nonslagging gasifiers, the maximum operating temperatures are set by the ash-softening temperatures. Therefore, coals with high ash-softening temperatures are preferred for the nonslagging gasifiers. Conversely, low ash-softening temperatures are desirable for slagging gasifiers. Gasifier performance, particularly the fixed- and entrained-bed units, is more sensitive to the fluctuation of the ash content in the coal feed.

Caking Tendency

The caking tendency of coals can be expressed by their free swelling index (FSI). The FSI is a measurement of the increase in volume of coal particles when the coal is heated under specified conditions. It is used to estimate the coal's caking properties during combustion and to differentiate between agglomerating and nonagglomerating coals. Single-stage fixed-bed gasifiers equipped with an agitator are capable of gasifying highly caking coals with an FSI up to 9.0. Agitated two-stage units have not been commercially demonstrated with strongly caking coal feed; therefore, two-stage fixed-bed units are currently limited to coals with an FSI of less than 3.0. Commercial fluidized-bed gasifiers (Winkler) cannot handle highly caking coals without an oxidative pretreatment step because ash agglomeration will result in defluidization of the gasifier. The pretreatment process reduces the coal's caking tendency by partial oxidation of the coal surface at the expense of using up to one-third of the volatile matter in the coal feed, as mentioned earlier. Entrained-bed gasifiers are not affected by the caking tendency of the coal feed because the overall gasification reactions are extremely fast and the contact time of small coal particles is very short.

Particle Size

For any given gasifier, there is usually an optimal particle size range for the coal feed. This size range is primarily determined by the gasifier's gas-solids contacting method. Fixed-bed gasifiers require relatively uniform coarse-sized coal feed. Undersized particles comprising more than 20 percent of the feed could cause operating problems such as gas maldistribution and excessive pressure drop which would reduce gasifier throughput and ultimately lead to a shutdown. The undersized fraction must be removed from the feed and used separately (e.g., as an auxiliary fuel for steam boilers). Coals with a high friability or grindability index, which tend to generate excessive fines in the feed preparation and handling operations, are not a desirable feedstock for fixed-bed units. Fluidized-bed units can use smaller, more size-variable coal feeds than the fixed-bed units. However, even in the fluidized gasifiers, care must be taken to ensure that fines do not exceed 20 percent passing through a No. 4 standard sieve. Fines in excess of this size will lower the thermal efficiency due to the carryover losses.

Other Major Components of Coal Gasification Plants

Coal Preparation and Handling System

The coal preparation and handling system receives and stores incoming raw coals, which are then prepared and delivered as a sized and dried feedstock to the gasifier. It typically consists of the following sections: raw coal unloading, raw coal storage, crushing, screening, and drying. A typical flow scheme is described as follows.

The incoming coal is dumped from the train into a multiple compartment track hopper by a rotary car dumper. Under normal operation, coal is conveyed from the track hopper directly to rows of concrete vertical, cylindrical, cone-bottomed storage bins. The storage capacity of these bins is up to 1 week full-

load operation. Some of the raw coal is stored in "dead-storage" as an emergency supply. In "dead-storage," coal is held in a compacted, sealed pile with a normal storage capacity of 1 month operation.

The outer surface of the coal pile in the "dead-storage" area is sprayed with an organic polymer crusting agent to prevent dusting or rain erosion. Crusting also prevents rainwater penetration of coal particles; thus, the water runoff has minimum contamination. The coal pile is located on a waterproof base to prevent water seepage into the ground. All runoff water is contained and used in the process.

The unloading facilities of raw coal are housed in a structure having various dust collecting equipment such as cyclones, bag filters, and precipitators to control particulate emission. The conveyors in the coal-handling system are completely enclosed and all conveyor junction towers have junction houses to completely enclose the coal transfer points. Each junction house has a dust collection system.

Raw coal is then crushed, sized, and dried in the coal preparation section before it is fed to the gasifier. Fixed-bed gasifiers require a coarse-sized feed between 1/4 and 1-1/2 in. The minus 1/4 in. fine coal fraction generated in the crushing operation is separated and used as auxiliary boiler fuel. Sized coal feed with a moisture content up to 35 percent can be fed directly to a fixed-bed gasifier.

Raw coal is crushed to 1/4 in. x 0 for fluidized-bed gasifiers, and is pulverized to 70 percent through 200 mesh for entrained-bed units. Operation of fluidized- and entrained-bed gasifiers is sensitive to the moisture content of the coal feed. Depending on coal rank, sized coal is dried to between 2 and 8 percent moisture to remove the surface water of the coal particles. Sized and dried coal is then stored in a storage silo with sufficient capacity such that any upsets in the coal preparation system will not interrupt gasifier operation. The entire coal preparation facility, including crushing, drying, and screening equipment, is enclosed in an essentially dust-tight building; the only exit for dust to the atmosphere is through the building ventilation and dust collector systems.

Individual equipment within the building is also fitted with dust collectors. The operating conditions of the coal dryer are controlled to maintain the coal particle temperatures below 200 °F to prevent the onset of chemical reactions or coal devolatilization. Therefore, the flue gases and water vapor generated in the drying process are not contaminated and can be discharged to the atmosphere after dust removal.

Coal Feed and Ash Removal Systems

Lockhopper systems are used to feed dry coal into the gasifiers with pressures up to 400 psig. Sized coal at atmospheric pressure is discharged by gravity from a storage bin into a hopper open at the top and closed with a valve at the bottom. After the hopper is filled, the valve at the top is closed and the hopper is locked and pressurized to the gasifier operating pressure. The bottom valve opens, and the coal falls by gravity either directly into the gasifier or into a surge hopper where it is then fed to the gasifier by some common feeding device such as a screw conveyor or star valves, or by a pneumatic conveying system. The use of the surge hopper provides continuous, steady coal feed to the gasifier. When the lockhopper is empty, the bottom valve is closed, the hopper is depressurized, and the top valve is opened to repeat the cycle.

Some high-pressure (up to 1100 psig) fluidized- and entrained-bed gasifiers use slurry feed systems. Ground coal mixes with a carrying medium such as water or light oil to make a slurry. The slurry is pumped to the gasifier pressure by a reciprocating pump. It then feeds through a pipe into a drying zone of the gasifier where the carrying medium is vaporized by the sensible heat of the ascending raw gas before the dried coal enters the gasifier's reaction zones. The carrying medium, now as part of the product gas, is condensed and separated from the product gas and reused.

Ash products are withdrawn from the bottom of the gasifier by the ash lockhopper system in essentially the same way that coal is introduced. The ash is then transported to a temporary storage silo prior to offsite disposal. If the ash is molten, it is quenched with water to break it up before discharging.

Raw Gas Cleanup System

Gas produced from the gasifier can be used in one of three forms:

- Hot raw gas
- Cold clean gas with sulfur removal
- Cold clean gas without sulfur removal.

Raw gas leaving the gasifier is first passed through a cyclone system to remove the carried-over particulates. The cyclone off-gas is the hot raw gas. This approach gives the highest thermal efficiency because there is no loss in the sensible heat of raw gas, and all combustible byproducts such as tars and oils are completely used. For successful operation, the hot raw gas must be used at a location near the gasifier to prevent condensation of tar/oil vapors in the gas line due to heat losses.

After dust removal, the hot raw gas flows through a heat recovery system. The heat recovered can be used to: (1) generate low-pressure steam in a waste heat boiler, (2) preheat the process air, or (3) exchange heat with the cold desulfurized gas. After heat recovery, the gas is quenched with water to condense out the tars/oils and excess water vapors. This step is followed by an electrostatic precipitator and a gas cooler, or a venturi scrubber, to remove particulates and traces of tar/oil droplets. The effluent gas is the cold clean gas. This gas has the lowest heating value because both the sensible heat of the gas and the heating values of the tar/oil vapors are lost. However, the cold clean gas is most suitable for longer transmission distances. Cold clean gas can be desulfurized in a typical sulfur removal system such as the Stretford unit if the sulfur content is too high.

In a two-stage fixed-bed gasifier, the top gas flows through a tar cyclone to remove large droplets of tar without cooling and the bottom gas passes through a dust cyclone to remove the entrained dust. The two gases are then combined, and the sensible heat in the bottom gas revaporizes the oil/tar mist in the top gas. The resultant gas is the hot raw gas. To produce a cold clean gas, the detarred top gas and the dedusted bottom gas are cooled with water directly or indirectly to further remove the particulates and condensibles before combining the two streams.

The tars and oils are separated from the condensed liquors collected at various points of the raw gas cleanup system and are recovered as byproducts in a gravity separation unit. The suspended solids are settled and removed for further treatment in the wastewater treatment system prior to disposal. Following removal of tars and oils, the water condensible components such as phenols and ammonia are recovered from condensed liquors by steam-stripping and solvent extraction processes.

The phenol can be extracted either before or after the water stripping, which is used to remove the dissolved gases from the wastewater by indirect reboiling of water with steam. A phenol extraction unit consists of a contacting column in which intimate contact is achieved between the wastewater and the solvent. The phenol-solvent mixture is then separated by distillation into a pure phenol product and lean solvent, which is recycled to the extraction column. The water from the extraction unit is steam-stripped, if required, to remove any trace solvent and is subsequently sent for further treatment or reused in the plant. The Lurgi-Phenosolvent and Chempro are commercially proven phenol extraction processes; both have been used on coal gasification plants and coke oven wastewaters.

Ammonia can be recovered directly from the wastewater or from the overhead vapors of the sour-water stripper. The ammonia is separated from the stripped gases in an absorber by absorption in an ammonia phosphate solution. The ammonia-rich solution is sent to a steam stripper where the ammonia is stripped off and recovered. The regenerated absorption solution is recycled to the absorber. The U.S. Steel (now USX) Phosam ammonia recovery process has been used successfully in coke oven gas-treating facilities and petroleum refineries.

Wastewater Treatment System

All wastewaters generated in the coal gasification process are treated at the plant site prior to discharge. The required treatment system is determined by the wastewater quality, which is directly related to the composition of raw coal and process parameters such as the design and operation of the gasifier and raw gas cleanup systems. A typical wastewater treatment system for a coal gasification plant is described as follows.

The wastewater is thickened by gravity clarification or air flotation to increase the suspended solids concentration. In the clarifier, the solids are settled from the wastewater by gravity and the effluent passes over the overflow weirs. The settled solids are removed along the base of the clarifier toward the center well by mechanical raking arms. Enough residence time is provided to allow the collected sludge to compact to a high concentration. Air flotation thickening is used when large amounts of floating solids are present in the wastewater streams. In a dissolved air flotation (DAF) unit, air is injected and dissolved into the recycled effluent wastewater stream in a pressurized retention tank. The air-saturated recycle stream is returned to the DAF influent after pressure letdown. The dissolved air flashes out and forms numerous minute air bubbles. The buoyancy of the solid particles is increased by the small rising air bubbles, and the solids-water separations are enhanced. Solids that rise to the surface are skimmed and collected for disposal or further treatment, if required.

The sludge from the thickening unit is sent to an anaerobic digestion unit to reduce the residual organic material and the pathogenic compounds. The organic compounds of the sludge are biologically converted to methane and carbon dioxide. These gases can be used to dry the final residue sludge prior to disposal.

The overflow water from the thickening unit is treated in an activated sludge system to reduce any biological oxygen demand (BOD) and to produce a high-quality effluent water for disposal. The wastewater is first mixed with the recycled activated sludge in an aeration tank. The recycled sludge consists of flocs whose surface is heavily colonized with bacteria, thus providing heavy inoculation of the incoming wastewater. The dissolved organic material is converted biochemically; the residue organic matter is settled from the purified water in a clarifier tank and recycled to the aeration tank. The effluent water is ready for final disposal.

Sulfur Removal System

In a coal gasification/gas-fired boiler plant, sulfur in the raw coal is converted to hydrogen sulfide (H_2S) and carbonyl sulfide (COS) in the fuel gas to the boiler, or to sulfur dioxide (SO_2) in the boiler flue gases. If the content of these pollutants is excessive, sulfur removal systems are required.

SO_2 can be removed from the boiler flue gas by conventional methods such as limestone scrubbing or the Wellman-Lord process. H_2S can be removed from the product gas and converted to elemental sulfur by the Claus or wet oxidation processes. It is easier to remove sulfur in the form of H_2S rather than SO_2. The need and degree of sulfur removal are determined by the sulfur content of the coal feed and the local and Federal environmental regulations.

The wet oxidation process is generally more economical than the Claus process because of the low H_2S content (usually less than 5 percent) in the cold clean gas. The Stretford process, a commercially available liquid phase oxidation process, is capable of removing essentially all H_2S in the gas. It will not, however, remove organic sulfur compounds such as COS and CS_2 which are usually present in coal-derived gas. If too much organic sulfur is present in the feed gas to the Stretford unit, it must be first converted catalytically by hydrolysis to H_2S and CO_2. Effluent gas from the catalytic hydrolysis reactor is then cooled and scrubbed with the Stretford solution—an aqueous mixture of sodium carbonate, sodium metavanadate, and anthraquinine disulfonic acid (ADA). H_2S is absorbed by the solution and converted to elemental sulfur through a series of fairly complex reactions. The liquor from the scrubber/absorber is regenerated by air-blowing in an oxidizer tank. The solid sulfur formed in the solution is removed from the oxidizer by froth flotation and recovered as a byproduct.

3 COMMERCIAL COAL GASIFICATION EQUIPMENT

Commercially proven coal gasifiers were reviewed. Findings are presented in terms of gasifier and process descriptions, gasifier operation and performance, raw gas cleanup requirements, typical coal feed characteristics and product gas compositions, commercial availabilities, and economic assessments. This review concentrates on the small fixed-bed gasifiers because their capacity ranges are most appropriate for retrofit to existing boilers at DOD facilities.

Commercial Fixed-Bed Gasifiers

Single- and two-stage fixed-bed gasifiers are generally designed to operate at or near atmospheric pressure. The two types of gasifiers differ mainly in the gas offtake configuration. The single-stage unit has only one product gas offtake at the top of the gasifier. In a two-stage unit, part of the gas is taken from the top, and the remaining gas is removed at a location below the top of the gasification zone. Both types of gasifiers generally consist of a stationary cylindrical shell and a revolving grate. Coal is fed by gravity either through lockhoppers or drum feeders mounted at the top of the gasifier. The revolving grate supports the bed at the bottom and also serves as a distributor for the reactant gases. Residue ash is removed at the bottom through an ash lockhopper system. A rotating agitator can be used in a single-stage unit for processing caking coal. The agitator breaks up agglomerates and also provides uniform distribution of coal feed across the bed. The gasifier vessel is either brick-lined or water-jacketed where high pressure steam is generated. There are many variations in mechanical design of the fixed-bed gasifier, but the basic principles are essentially the same.

Gas generated from the gasifier can be used as hot raw gas, cold clean gas with sulfur removal, or cold clean gas without sulfur removal. The composition and heating value of the product gases generated from a single- or a two-stage unit are not significantly different. The two-stage unit produces higher quality oils and tars because of the slower heatup and devolatilization of the coal feed. There are no commercialized two-stage units equipped with an internal agitator; only single-stage units can handle both caking and noncaking coals.

Operation of a fixed-bed gasifier is generally simple and automatic. Typically, an operating staff of two is enough to handle a gasification plant using two or three gasifiers, whether they are single- or two-stage units, large or small. Coal feed is usually maintained at a constant rate regardless of the load change. Product gas flow rate is controlled by regulating the air flow rate to the gasifier. Ash is discharged by the revolving grate system. Additional control is required in two-stage gasifiers to regulate the relative flowrate of the top gas and bottom gas such that the top gas temperature is maintained at around 250 °F. The maintenance schedules for single- and two-stage gasifiers are comparable. Normally, both types have scheduled annual shutdowns for meeting boiler code requirements and for regular maintenance. The agitator wear-bars of single-stage gasifiers need to be inspected periodically.

Single-Stage Fixed-Bed Gasifiers

Simplicity is the key advantage of a single-stage fixed-bed gasifier. It results in lower construction costs, stable operation, and ease of maintenance. In addition, all types of coal can be gasified directly in the agitated unit. However, heavy tars are produced due to rapid devolatilization of raw coal at high temperatures which can cause tar buildup and troublesome operations in raw gas cleanup systems. The existing small commercial units have not been pressurized, so that product gas compression may be required before end use. Usually the gasifier can accept only up to 15 percent of fines in the coal feed. This may represent serious restrictions with certain coal types.

Single-stage fixed-bed gasifiers have been in use the longest and are also the best known among all coal gasification processes. It is the only coal gasification technology being used commercially in the

United States. There are many variations in design, but the principles are essentially the same. The Wellman-Galusha, Wilputte, and Riley-Morgan gasifiers were reviewed for this study.

Wellman-Galusha Gasifier.[4] Crushed coal is fed to the gasifier through a two-compartment coal bin and vertical feed pipes located at the top of the gasifier (Figure 10). The coal bin operates on the same principles as the lockhopper system. The upper compartment acts as a storage hopper while the lower one is the feed hopper. Slide-gate valves are used to maintain a constant coal feed rate to the gasifier. Ash is discharged continuously from the bottom of the gasifier into the ash hopper by the revolving grates (Figure 11). The grates are constructed of flat circular steel plates set one above the other with overlapping edges. The grates are eccentric with the center support, and the entire assembly rotates very slowly. Due to this eccentricity, ash is forced horizontally through the vertical space between the stepped plates. This action provides a steady flow of crushed ash into the ash hopper. The ash and combustion zone depths are determined periodically by poking and are maintained at a constant level by controlling the speed of grate and ash discharge rate.

The gasifier is completely water-jacketed. Gasification air, provided by a fan, passes over the steaming water at the top of the jacket and picks up the necessary steam for gasification. The air-steam mixture is introduced into the ash hopper and distributed through the grate into the bed. The steam/air ratio is controlled by the blast saturation temperature (BST) of the steam-air mixture. The BST is controlled by the flow rate of the water supply to the gasifier water jacket. It is maintained between 150 and 180 °F.

For highly caking coal, an agitator with a slower revolving horizontal arm that also spirals vertically below the surface of the coal bed can be installed in the gasifier (Figure 12). The agitator arm and vertical shaft are water-cooled and the wearing parts are protected by heat- and wear-resistant castings. The agitator provides more uniform solids distribution and reduces gas channeling within the coal bed, thus increasing gas production over a nonagitated unit. The rated capacity of an agitated unit is about 25 percent higher than that of a standard unit of the same size.

The gasifier can be used to gasify anthracite, lignite, bituminous, or coke. Caking coals with an FSI as high as 9 have been gasified successfully in agitated units. Although an ash-softening temperature above 2200 °F is preferred, lower values can be handled with a reduction in the coal throughput and efficiency. Table 3 lists typical characteristics and proximate analyses of coal feeds. For a typical air-blown operation, 3.12 lb air/lb of coal and 0.516 lb steam/lb of coal are used for the gasifier. The gasifier bed temperatures are controlled by the air/steam ratio. Raw gas leaves the gasifier at temperatures between 800 and 1200 °F, depending on the coal type, and is at a pressure of 5 to 6 in. of water. The gasifier has a turndown capability of 13 to 1. Figure 13 is a schematic process flow diagram.

Raw product gas can be used in any one of the three forms: hot raw gas and cold clean gas with or without desulfurization. The raw gas leaving the gasifier at about 900 to 1200 °F is first passed through a refractory-lined cyclone to remove most of the particulates. Hot raw gas leaving the cyclone can be used directly. The heating value of this gas ranges from 160 to 210 Btu/SCF with a thermal efficiency of about 93 percent.

After the cyclone, the gas exchanges heat with the cold, desulfurized gas or flows through a waste heat boiler for heat recovery, and is then quenched with water in a quench drum to condense the tar and oil vapors present in the hot raw gas. The gas from the quench drum passes through an electrostatic precipitator to remove traces of particulates and then through a gas cooler to remove traces of oil. The gas leaving the cooler is cold clean gas. The tar, oil, and water containing ammonia and other traces of

[4] Gilbert/Commonwealth Co.; McDowell-Wellman Engineering Co., *Wellman-Galusha Gas Producers*, Brochure No. 576; W. W. Bodle and J. Huebler, Coal Gasifications, R.A. Meyers (Ed.) (Marcel Dekker, 1981).

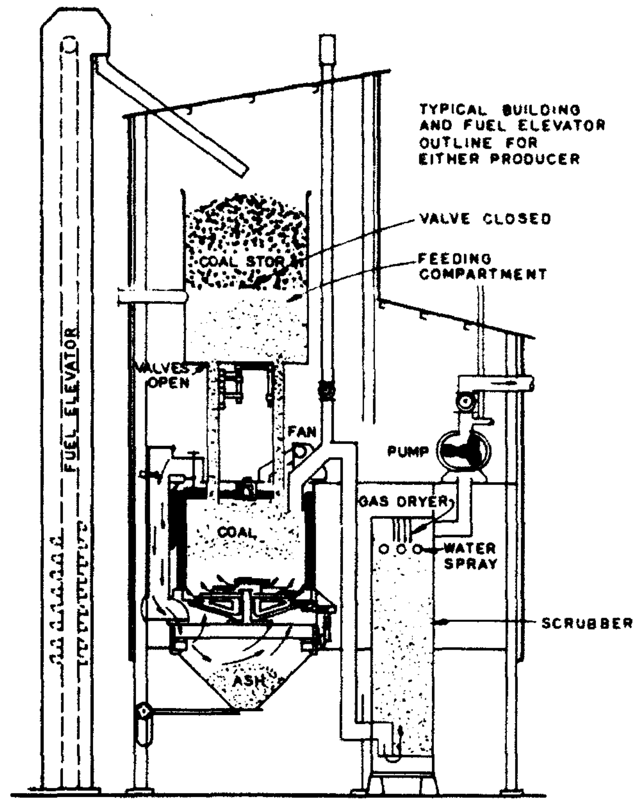

Figure 10. Wellman-Galusha standard-type gasifier.

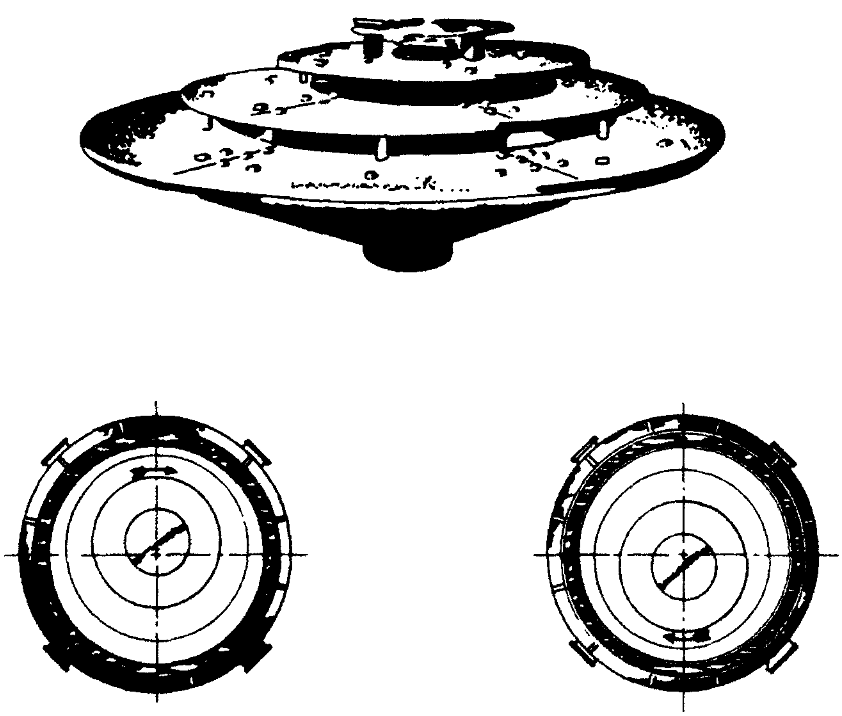

Figure 11. Wellman-Galusha revolving grates.

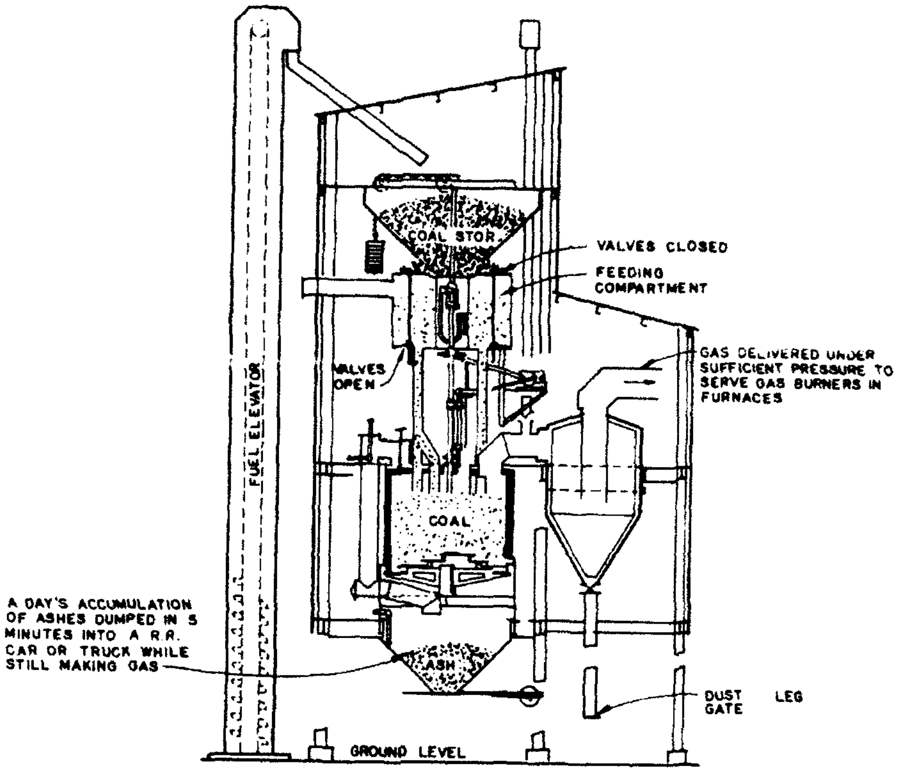

Figure 12. Wellman-Galusha agitator-type gasifier.

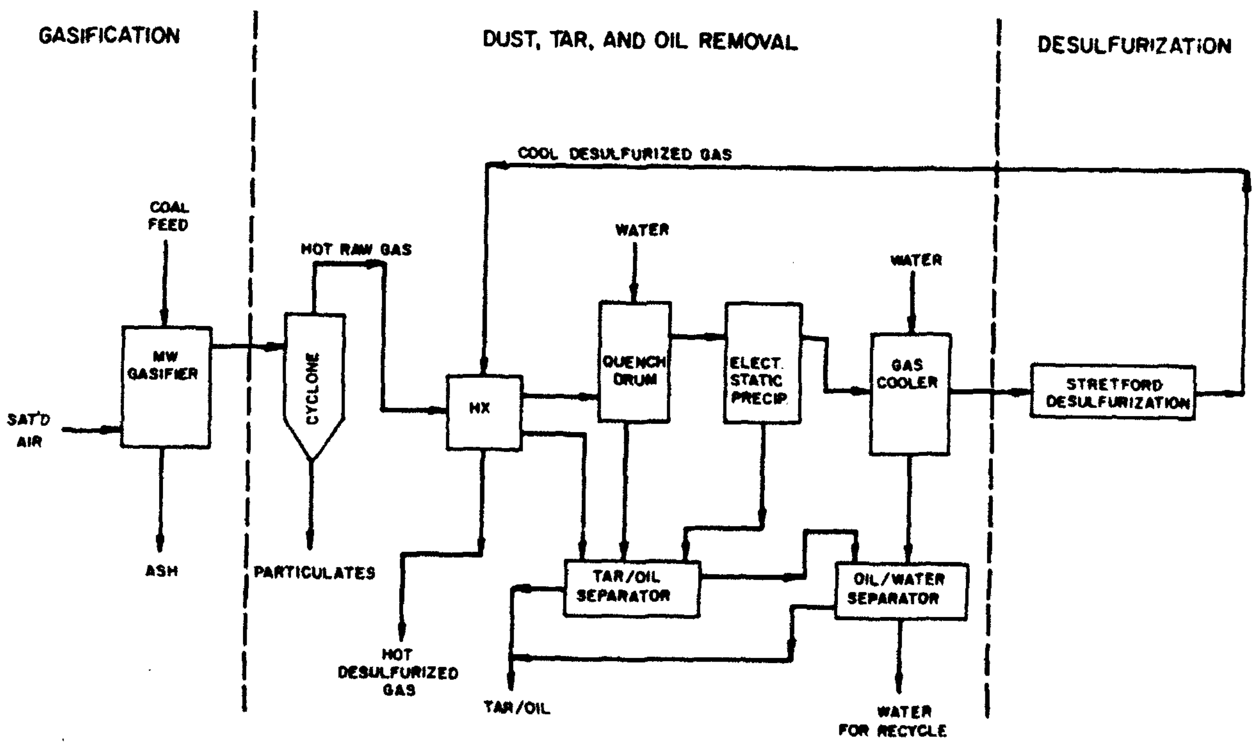

Figure 13. Wellman-Galusha fuel gas process.

Table 3

Typical Coal Feed Characteristics For Single-Stage Wellman-Galusha Gasifier

Size	• 3/16" to 9/16" for anthracite		
	• 1-1/4" to 2" for bituminous coal		
	• 1/4" to 5/8" for coke charcoal		
	• Fines not more than 30%		
FSI	**No limit**		
Ash Fusion Temperature	**Greater than 2,100 °F**		
Typical Coals			
Proximate analyses, %	Anthracite	Coke	Bituminous
Moisture	4.2	5.0	1.4
Volatile matter	4.4	-	30.1
Fixed carbon	80.7	83.1	58.5
Ash	10.7	11.9	10.0
Total	100.0	100.0	100.0
Sulfur Content, wt %	0.6	0.6	3.2
HHV, Btu/lb	12,700	16,000	13,400
Feed Rate (Air-blown), TPD			
Diameter, ft			
3.5 Standard	2.6	2/9	-
6.5 Standard	9.2	10.0	-
6.5 Agitator	11.5	12.4	34.8
8.0 Standard	13.8	15.0	-
10.0 Standard	22.1	24.0	-
10.0 Agitato	27.6	30.0	84.0

*HHV = higher heating value.

impurities are sent to a tar/oil gravity separator. The heavy tars and solids settle to the bottom and are sent to a tar/oil storage tank. The aqueous layer containing oil is taken to a second settling tank and the oil layer is decanted to the tar/oil storage tank. The aqueous effluent containing ammonia and phenol is steam-stripped, and the purified water is recycled for use in the gasifier jacket, the quench, and cooling units. Cold clean gas leaves the gas cooler at about 120 °F having a heating value of 146 to 170 Btu/SCF. Thermal efficiency ranges from 71.6 to 85.6 percent, depending on the type of coal used. The cold clean gas can be used as is or can be desulfurized in a Stretford unit if the sulfur content is too high.

Medium-Btu gas with a heating value of 250 to 300 Btu/SCF can be produced using oxygen instead of air. The process schemes of the raw gas cleanup system are the same as described above. Table 4 lists characteristics of the typical medium-Btu product gas. Table 5 is a 25-year listing of commercial installations in North America that use the Wellman-Galusha gasifiers. Dravo Engineers, Inc. has constructed a fully instrumented, 3-ft internal diameter Wellman-Galusha pilot gasifier. The unit is equipped for online gas sampling and a gas chromatograph is used for online monitoring. In addition, the gasifier has ports for tar and sulfur sampling and a special sample port for isokinetic probe sampling to obtain dust loading information in the product gas stream. The gasifier can operate on a wide range of solid fuels from anthracite to wood. The internal and external configurations of the gasifier can be changed to optimize operation for any given solid feedstock.

Table 4

Typical Product Gas Characteristics Available From Single-Stage Wellman-Galusha Gasifier

Composition, Vol. %	Low-Btu Gas	Medium-Btu Gas
H_2	18.7	36.25
CO	24.9	47.05
CO_2	6.2	13.90
CH_4	0.6	0.65
N_2	49.3	2.05
Others	0.3	0.10
Total	100.0	100.00
HHV,* Btu/SCF		
Hot raw gas	160-210	
Cold clean gas	146-170	258-270
Temperature, °F		
Hot raw gas	800-1,200	-
Cold clean gas	120	120
Thermal efficiency, %		
Hot raw gas	93	-
Cold clean gas	71.6-85.6	-
Gas product rate, SCF/lb coal	50-75	-
Byproduct rate		
Tar/oil, lb/lb coal	0.06	-

*HHV - higher heating value.

Wilputte Gasifier.[5] The Wilputte gasifier, as shown in Figure 14, is used to gasify various types of coal at atmospheric pressure. For bituminous coal, the gasifier is brick-lined and equipped with a Chapman rotating drum feeder and agitator assembly. The rotating agitator equipped with a water-cooled rabble arm provides better solids mixing and more uniform gas distribution in the bed compared with nonagitated beds. For coke or anthracite, a cyclic batch feed is used and the gasifier is water-jacketed. Residue ash is discharged continuously from the bottom of the gasifier into a revolving ash pan by the rotating grate equipped with spiral ribs. A stationary ash plow removes the ash from the ash pan and forces it into the ash hopper. The rotating grate and ash pan assembly ride on three sets of roller supports. The gasifier shell is supported above the grate and ash pan by columns. The gasifier is sealed by water in the ash pan. This water also aids in breaking up cinders and in cooling the ash. Two standard diameters of Wilputte units, 9 ft-2 in. and 10 ft-4 in., are available. Both units are 16 ft-5 in. high.

[5] Gilbert/Commonwealth Co.; G.R. Cooper, "Operating Overview of a Producer Gas Plant at Kingsport, Tennessee," presented at the 5th Annual International Conference on Coal Gasification, Liquefaction, and Conversion to Electricity, University of Pittsburg (August 1978).

Table 5

Commercial Experience for Wellman-Galusha

Company/ Location	No. of Units	Gasifier Diameter, ft	Coal Type	Scope of System	Application	Status
Gypsum Lime Ltd. Beechville, OH	1	10 with agitator	Bituminous	Low-Btu	Lime kiln	Inoperative since 1965
Stelco Limited Beechville, Ont.	1	10 with agitator	Bituminous	Low-Btu	Heat treating furnace	Inoperative since 1963
Mississippi Lime, St. Genevieve, MO	1	10 with agitator	Bituminous	Low-Btu	Lime kilm	Inoperative since 1964; in place
Union Carbide, Nopco Chemical Div. Linden, NJ	1	3.5	Coke	Med-Btu	Chemical Feed Stock	Inoperative; in place
NL Industries National Lead Div. South Amboy, NJ	1	2	Coke	Med-Btu	Chemical Feed Stock	Inoperative since 1966; in place
Allied Chemical, Ltd. Corunna, Ont.	1	3	Bituminous	Low-Btu	Fuel Gas	Inoperative
New Jersey Zinc Ashtabula, OH	1	6.5 with agitator	Coke	Med-Btu	Chemical Feed-stock-Production of Titanium Dioxide (TiO_2)	Operative
U.S. Bureau of Mines Morgantown, West	1	3.5	Bituminous/ Lignite	Low/Med-Btu	Experimental with 300 psi pressure	Operative
U.S. Bureau of Mines Twin Cities, MN	1	10	Bituminous/ Lignite	Low-Btu	Iron ore pellet kilns (induration of iron ore)	Operative
Olin - Mathieson Ashtabula, OH	1	5'	Petroleum Coke	Med-Btu	Feedstock in producing phosgene	Operative
Riley-Stoker Worcester, MA	1	2	Bituminous anthracite coke, lignite	Low-Btu	Performing with various coals	Operative
Glen-Gary Corp. Reading, PA	12	10 with agitator	Anthracite	Low-Btu	Brick kiln firing	Operative
National Lime & Stone Co. Carey, OH	2	10 with agitator	Bituminous	Low-Btu	Lime kiln	Operative
Pikeville Energy Ctr Pikeville, KY	1	6.5 with agitator	Bituminous	Low-Btu	Commercial fuel gas	1979 Operative
Can Do, Inc. Hazelton, TA	2	6.5	Anthracite	Low-Btu	Industrial fuel gas	1979 Operative
Tiwan Fertilizer, Co. Formosa	7	10 with agitator	Korean anthracite	Med-Btu	150 TPD NH_3 prod.	Operative
Nickel Processing Corp.	14	10	Bituminous	Low-Btu	Industrial fuel gas	Operative

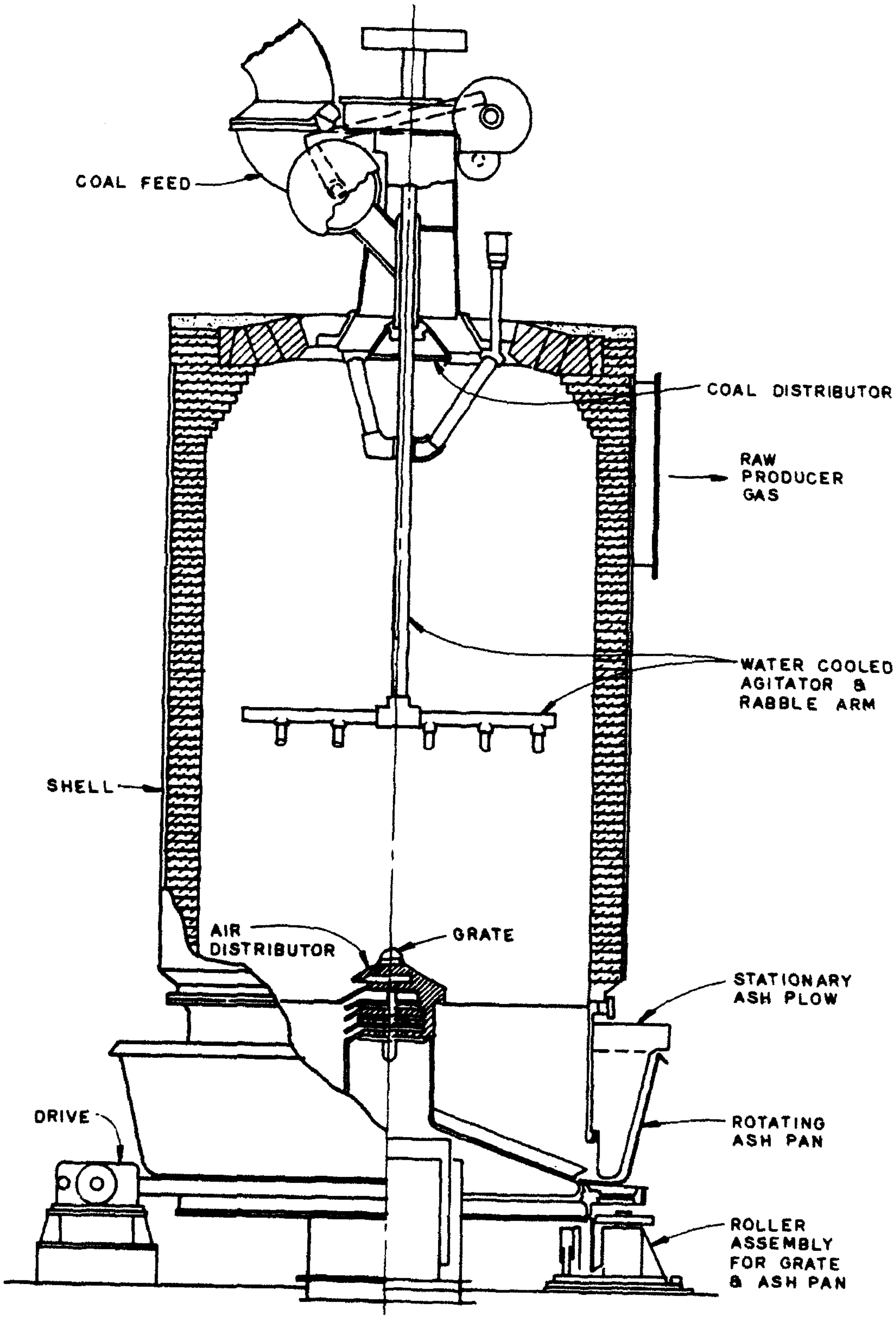

Figure 14. Wilputte gasifier.

Bituminous, subbituminous, anthracite, and coke have all been gasified in the Wilputte gasifier. Raw coal is typically crushed to 3 to 4 in. for all coal types; 1-1/2 to 4 in. can also be used with up to 10 percent fines. The highest FSI of coal used is 6. The ash fusion temperatures must be greater than 2300 °F. Table 6 summarizes typical coal feed characteristics along with a bituminous coal analysis used in the Wilputte gasifier.

Air to the gasifier is saturated with steam from the gasifier water-jacket or from an outside source. For a typical air-blown operation, 3.31 to 3.67 lb air/lb of coal and 0.53 lb steam/lb of coal are used for the gasifier. The air/steam ratio is controlled to maintain a BST of 140 °F. A gas pressure controller regulates the flow rate of the steam-air mixture in response to a change in the demand of product gas. Raw gas leaving the gasifier is at 1200 °F and at a pressure of 2 to 4 in. water for bituminous coal. The turndown capability is 10:1 at maximum capacity.

Three different product streams—hot raw gas and cold clean gas with or without desulfurization can be produced in the Wilputte system. Figure 15 is a schematic process flow diagram. Raw gas from the gasifier passes through a dust collector to produce hot raw gas. This gas has a high heating value of 207 Btu/SCF and a thermal efficiency of 90 percent including the sensible heat and the heating values of tars and oils. The hot raw gas flows through a waste heat boiler for heat recovery and is then sent to a wet scrubber to condense tars and oils. The scrubbed gas is taken to the electrostatic precipitator to remove traces of tars and oils. The gas leaving the electrostatic precipitator is the cold clean gas, which has a heating value of 170 Btu/SCF and a thermal efficiency of 80 percent. The tar is separated from the scrubbing liquor in a decanter, which is also provided with a slow-moving rake to remove the settled solids. The byproduct tar is continuously removed from the decanter and recovered as auxiliary boiler fuel. The scrubbing liquor is recycled to the wet scrubber after an exchange cooler. The hot raw gas can be desulfurized in a standard sulfur removal process such as the Stretford unit, if necessary.

Table 6

Typical Coal Feed Characteristics for Single-Stage Wilputte Gasifier

Size	3 - 4 in.
	Fines up to 10% acceptable
FSI	Up to 6
Ash fusion temp., °F	Greater than 2300
Typical coal	Bituminous
Proximate analysis, %	
Moisture	3.28
Volatile matter	35.31
Fixed carbon	55.87
Ash	5.54
Total	100.00
Sulfur, wt %	0.47
HHV, Btu/lb	12,200
Feed rate, TPD	60 for 10 ft-4 in. diam. air-blown gasifier

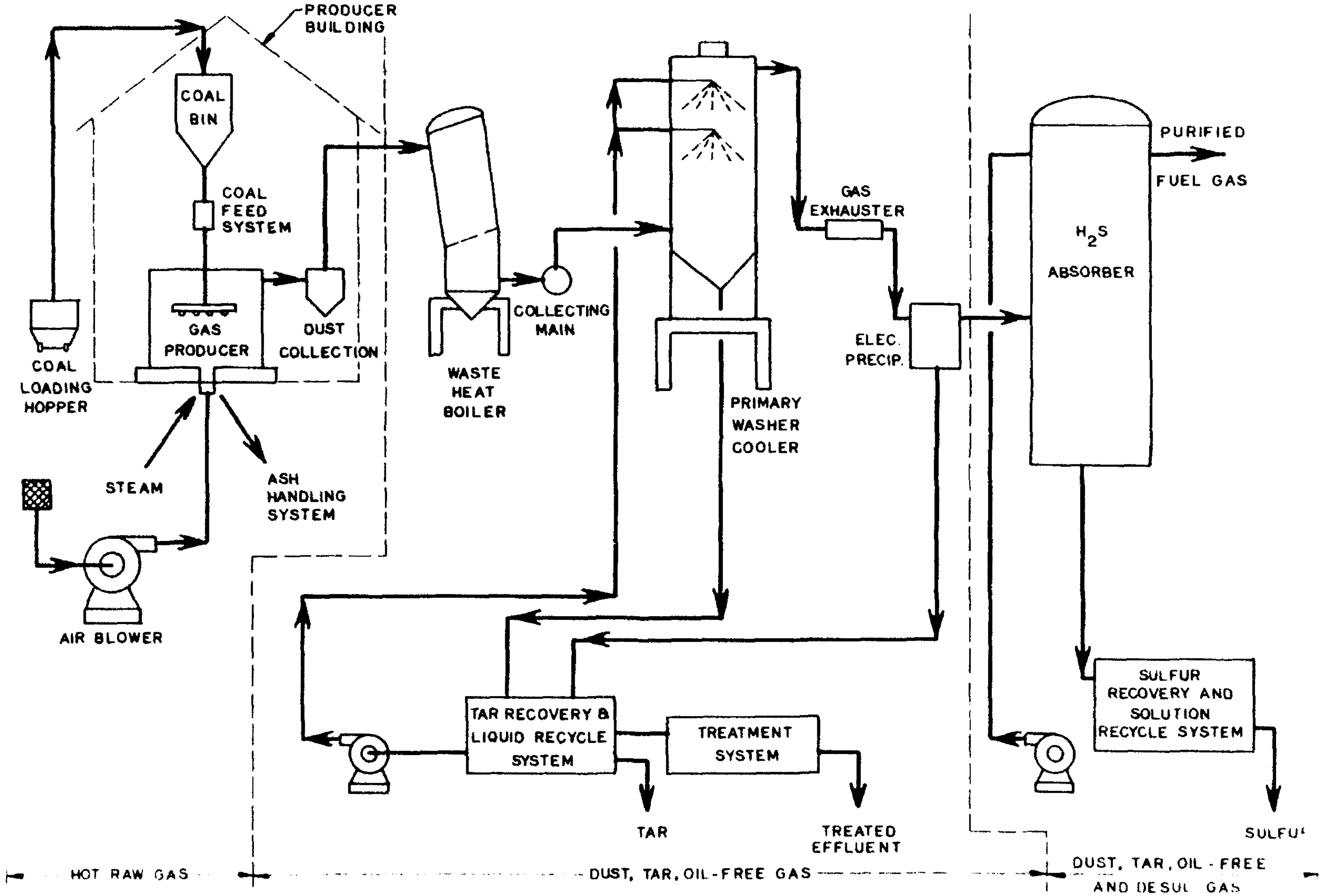

Figure 15. Wilputte coal gasification process.

An air-blown, 9 ft-2 in.-diameter gasifier will produce 2.9 million SCF/day of 165 Btu/SCF fuel gas from 24 ton/day of bituminous coal. If oxygen is used, the product gas will be approximately 300 Btu/SCF. Table 7 lists characteristics of product gas. Table 8 is a partial listing of Wilputte gasifier users.

Riley-Morgan Gasifier.[6] The Riley-Morgan gasifier chamber is a refractory-lined cylinder that rotates slowly in a water seal (Figure 16). Sized coal is fed to the gasifier through a lockhopper system and a metering drum feeder. The raw coal is distributed evenly on top of the bed by the rotating barrel and pivoting leveler arms. The leveler arms also sense the position of the bed top which controls the ash discharge rate. Table 9 lists typical coal feed characteristics for single-stage Riley-Morgan gasifiers. Ability to operate at various bed heights together with the agitator assembly makes operation with caking coal possible. There is no grate in the gasifier; the ash bed functions as a grate. Ash is removed from the bottom of the gasifier through a water seal by means of a helical plow in the rotating ash pan.

Table 7

Typical Product Gas Characteristics Available From Single-Stage Wilputte Gasifier

Composition, Vol. %	Low-Btu Gas
H_2	16.6
CO	22.7
CO_2	5.9
CH_4	3.6
N_2	50.9
Others	0.3
Total	100.0
HHV, Btu/SCF	
Hot raw gas	207
Cold clean gas	170
Temperature, °F	
Hot raw gas	1,200
Cold clean gas	120
Thermal efficiency, %	
Hot raw gas	90
Cold clean gas	80
Gas Product rate, SCF/lb coal	57.3
Byproduct rate, lb/lb coal	
Tar	0.1
Oil	0.2

[6] Gilbert/Commonwealth Co.; W.P. Earley, R.A. Lisauskas, and A.H. Rowdon, "Practical Operating Experience on a Riley Gasifier," presented at the 88th National Meeting of the American Institute of Chemical Engineers, Philadelphia (June 1980).

Table 8

Partial Listing Of Typical Commercial Experience For Wilputte Gasifier*

Company/ Location	Capacity: No. of Units	Capacity: Gasifier Diameter, ft	Capacity: Heat Rate 10^9 Btu/Day	Coal Type	Application	Date & Comments
Perth Amboy, NH Municipality	1	6.6	—	—	—	1918
Pennsylvania Gas and Water	1	—	—	Converted water gas machine	High Btu (1000 Btu/cf) oil gas machines	
Paccal (Australia)	2	—	—	—	High Btu (1000 Btu/cf) oil gas machines	
Semet Solvay Ironton, OH	2	9.3	0.8 Total	Coke	Underfiring B.P. coke ovens	1930
Staten Island Shipbuilding Staten Island, NY	1 1	6 9	—	—	—	1912
Tennessee Eastman Kingsport, TN	2	9.2	—	Bituminous	Chemical operations	1933 36 TPD of coal
Virginia Carolina Chemicals Charleston, SC	1	9.2	—	Coke	Furnaces	1933, 1600 lb/hr of coke
Eastern Rolling Mills Baltimore, MD	1 2	5.5 9.2	— 0.2 each	Anthracite, #1 Buckwheat anthracite	Heating rolls normalizing furnace	1917 1925
Jefferey Mfg. Co. Columbia, OH	1	10.5	0.4	Bituminous	Heating treating gas engines	1929
Allis Chalmers of Canada	4	1-4.5 2-5.0 1-5.5	—	Anthracite	—	1913 to 1917
A.O. Smith Milwaukee, WI	1	9	—	—	—	1912
Citizens Light Heat & Power Cangy, MN	1	9	—	Buckwheat anthracite	Utility station	1917
Dupont Carney's Pt., NJ	3	9.2	0.3 each	#1-Buckwheat anthracite	Chemical operations	1927 to 1930
Ford Motor Company of Canada Walkersville, Ont.	3	9.2	—	Bituminous	Heat tracing	1926, 1500 lb/hr coal each
General Electric Erie, PA	1	5.5	—	—	—	1917
Holston Defense Corporation Kingsport, TN	12	9.1	—	Bituminous	Furnaces	1945, 4 operating
International Harvester	3	3.5 4.0 5.0	—	—	Test use	1910 to 1911
Johns Hopkin Univ. Baltimore, MD	1	3.5	—	-	Test use	1915
Kellog Company Battlecreek, MI	2 (plus 7 other 9'0" size)	9.5	0.2-0.3 each	#1, #2, #3 Anthracite buckwheat	Roasting food products	1927 to 1930
Long Island Lighting Co , NY	1	—	—		High Btu (1000 Btu/cf) oil gas machines	

* Data for plants sold from 1934 to 194' are incomplete.

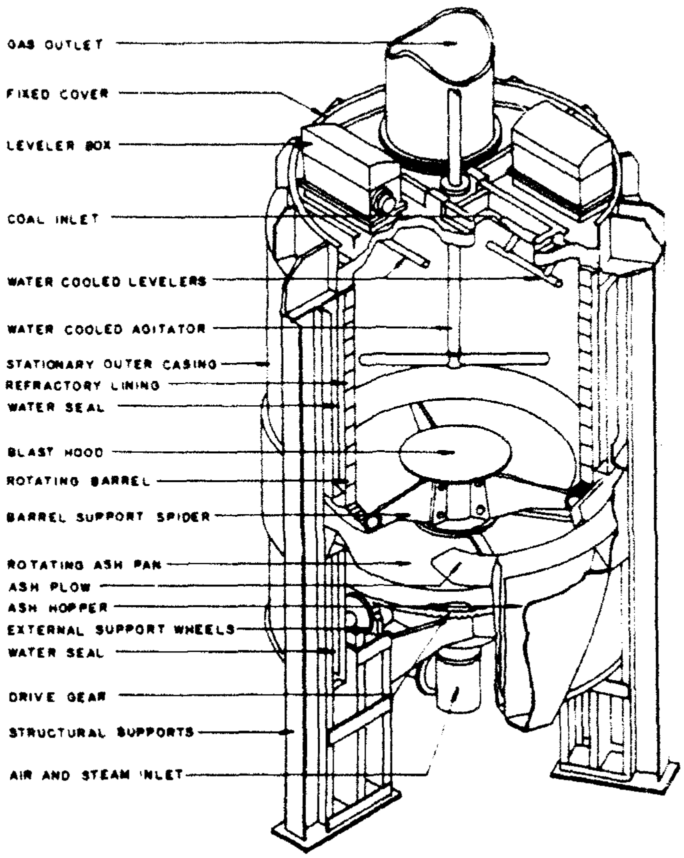

Figure 16. Riley-Morgan gasifier.

Table 9

Typical Coal Feed Characteristics for Single-Stage Riley-Morgan Gasifier

Size	• 3/8" to 5/8" for anthracite		
	• 1-1/4" to 2" for bituminous coal		
	• 3/4" to 1-1/2" for coke		
	• Up to 10% fines acceptable		
FSI	• Up to 8-1/2"		
Ash Fusion Temp., °F	• Bituminous — 2400 • Anthracite — 2700		
Typical Coals Proximate Analysis, %			
	Anthracite	Coke	Bituminous
Moisture	3.95	9.2	3.43
Volatile Matter	4.45	1.0	30.93
Fixed Carbon	81.70	81.2	53.81
Ash	9.90	8.6	11.83
Total	100.00	100.0	100.00
Sulfur, wt %	0.7	1.0	0.9
HHV, Btu/lb	12,700	16,000	13,400
Feed Rate (10'-6" dia.), TPD			
Air-blown	36-48	50.4	90
Oxygen-blown	61-82	85.2	156

The air-steam mixture enters the gasifier at the bottom of the rotating ash pan and is distributed across the bottom of the bed by a blast hood. For air-blown operation, the air requirement ranges from 2.98 to 3.44 lb/lb coal and the steam requirement is 0.56 lb/lb coal with a BST between 142 and 147 °F. For oxygen-blown operation, the gasifier requires 0.6 to 0.7 lb oxygen/lb coal and 1.3 to 1.5 lb steam/lb coal. Turndown capability is 10:1 based on maximum capacity. Operating test conditions and results of a full-scale (10 ft-6 in.-diameter) unit are summarized in Table 10 for eastern bituminous and northern Great Plains lignite coals.

The process schematic diagram of the Riley-Morgan gasification system, as shown in Figure 17, produces three product streams: hot raw gas and cold clean gas with or without sulfur removal. The gas leaving the gasifier passes through a dust collector where particulates are removed. The hot raw gas is at a temperature of 1100 °F and at 40 in. of water pressure. Depending on the coal type, the hot raw gas has a heating value of 185 to 201 Btu/SCF for air-blown and 262 to 305 Btu/SCF for oxygen-blown gasifiers. A thermal efficiency of 88 to 90 percent is obtained for air-blown gasifier operation.

The hot raw gas is then cleaned and cooled to remove heavy tars in the direct quench and the lighter tars in the indirect cooler. This step is followed by an electrostatic precipitator to remove trace tar droplets. The light oils are removed in a light oil absorber. The cold clean gas yields a heating value of 138 to 163 Btu/SCF and a thermal efficiency of 70.5 to 78.3 percent, depending on coal types used. Gas leaving the light oil absorber is fed to a Stretford unit for removal of sulfur components, if necessary. Typical product gas characteristics obtained from the Riley-Morgan gasifier are summarized in Table 11.

Although no Riley-Morgan gasifier has been operated commercially, the Morgan Gas Producer, its forerunner, was employed until 1941 by more than 9000 producers worldwide. Units installed in 1933 and 1948 are currently operating in South Africa. In 1980, gasification tests were conducted successfully in a 10 ft-6 in.-diameter demonstration unit using anthracite and bituminous coals. This demonstration unit, built by Gilbert/Commonwealth, represents a commercial-scale gasifier.

Two-Stage Fixed-Bed Gasifiers

The two-stage fixed-bed gasifier consists of a tall, refractory-lined drying and devolatilization section at the top and a relatively short, water-jacketed gasification and combustion section at the bottom. A portion of the gas produced in the gasification section is removed before entering the devolatilization section. This gas is withdrawn at 1100 to 1200 °F and is called the "bottom gas." The rest of the gas passes through the devolatilization section, exits the top at 250 to 300 °F, and is called the "top gas." The flow rate of the top gas, i.e., the main heat source for drying and devolatilizing the raw coal, is controlled by regulating the flow rate of the bottom gas. Since the devolatilization section is tall and nearly filled with coal, the raw coal is heated and devolatilized slowly at moderate temperatures. The devolatilization products therefore are not subjected to rapid heating and high-temperature cracking and polymerization. Tars/oils of lower viscosity in the form of fine mists are produced in this process. The better quality of tar/oil products simplifies the design and operation of the raw gas cleanup system.

The two-stage gasifier is not equipped with an agitator; therefore, it cannot directly handle highly caking coals. To prevent bridging of weakly caking coals, the devolatilization section is usually tapered toward the top or is divided vertically into compartments. Similar to the single-stage units, the rotating grate is used to remove ash as well as to distribute the reactant gases. The ash is then withdrawn by lockhoppers or through a water-sealed ash pan.

Table 10

Summary of Operating Conditions and Results of a 10.5-ft Diameter Riley-Morgan Gasifier

	Eastern Bituminous	Northern Plains Lignite
Coal Data		
Size (Nominal)	2" x 1-1/2"	2" x 1/2"
Moisture (as received) wt %	4.3	32.8
ash (dry) wt %	3.9	9.8
Volatile Matter (dry) wt %	41.1	42.0
Fixed Carbon (dry) wt %	55.0	48.2
Higher heating Val;ue (dry) Btu/lb	14,570	10,760
Ash Softening Temperature, °F		
(Reducing H = 1/2W)	2,600	2,020
(Oxidizing H = 1/2W)	+2,700	2,190
Free Swelling Index	4.5	0
Operating Conditions		
Air, lb/lb daf coal	3.11	2.44
Steam/Air Ratio wt/wt	0.14	0.18
Fuel Bed Height, inches	46	48
Operating Results		
Outlet Temperature, °F	1,292	518
Gas Yield SDF/lb daf coal	69.3	56.1
Gas Heating Value Btu/SCF	156	166
Tar Yield lb/lb feed coal	0.087	0.02
Moisture lb/lb feed coal	0.25	0.44
GASIFICATION EFFICIENCIES		
(a) Heating Value of Raw Gas x 100 / Heating Value of Gasified Coal	71.4	78.0
(b) Raw Gas x 100 / Gasified Coal + Steam	69.0	74.9
(c) Raw Gas + Tar + Oil x 100 / Gasified Coal + Steam	78.3	77.9
GAS COMPOSITION (VOL. %) SATURATED AT 60 °F, 30" Hg		
CO	21.6	28.1
CO_2	7.5	6.1
H_2	13.9	17.3
CH_4	2.2	1.5
CnHm	0.9	0.2
COS & H_2S	0.1	0.1
Inerts	0.6	0.5
N_2	51.5	44.5
H_2O	1.7	1.7
	100.0	100.0
Higher Heating Value (Btu/ft^3)	156	166
CO/H_2 Ratio (Vol/Vol)	1.55	1.62

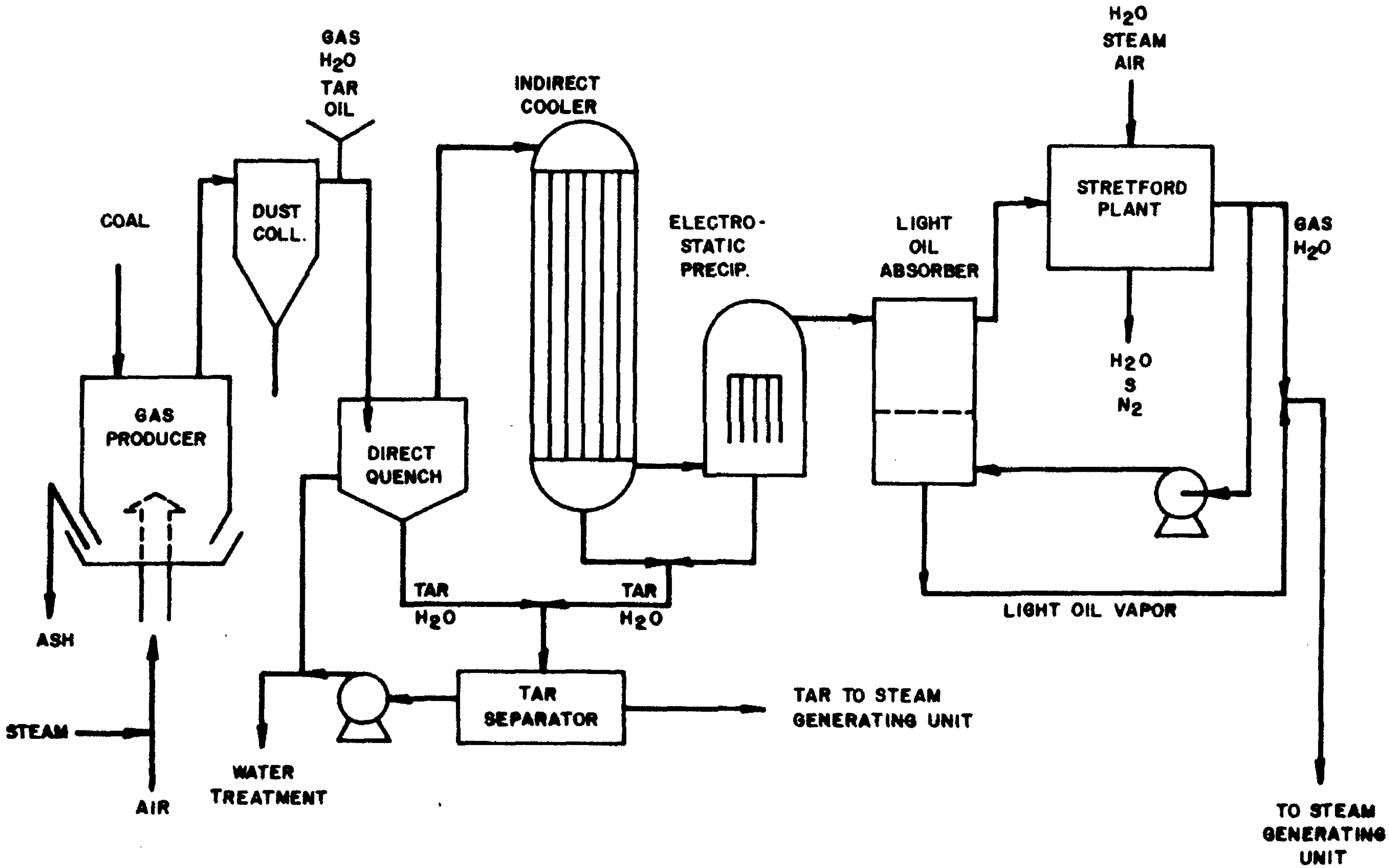

Figure 17. Riley-Morgan low-Btu gas plant flow diagram.

Table 11

Typical Product Gas Characteristics Available From Single-Stage Riley-Morgan Gasifier

Composition, Vol. %	Low-Btu Gas	Medium-Btu Gas
H_2	18.7	39.2
CO	24.9	41.3
CO_2	6.2	17.5
CH_4	0.6	1.4
N_2	49.3	0.6
Others	0.3	0.0
Total	100.0	100.0
HHV, Btu/SCF		
Hot raw gas	185-201	
Hot detarred gas	165-179	
Cold clean gas	138-163	262-305
Temperature, °F		
Hot raw gas	1,080-1,100	1,100
Cold clean gas	120	120
Thermal Efficiency, %		
Hot raw gas	88-89.9	
Cold clean gas	70.6-78.3	75.0
Gas product rate, SCF/lb coal	58-63	28
By-product rate, lb/lb coal		
Tar	0.078	0.078
Oil	0.009	0.009

Coal feed is controlled to maintain a constant level in the devolatilization section. The steam/air ratio is controlled by the BST of the steam-air mixture. The BST is usually set between 130 and 140 °F. A pressure controller in the product gas distribution main regulates the flow rates of steam and air in response to demand change of product gas. The speed of the rotating grate is controlled to maintain a proper ash discharge rate and ash bed depth. This feature protects the grate from overheating. The ash and fire bed depths are determined periodically by hand-poking. A steam curtain is provided during poking to minimize gas leakage through the poke holes. The two-stage unit can be turned down to about 30 percent of its design capacity and can be brought back to full capacity within 30 min.

The Woodall-Duckham, ATC/Wellman-Incandescent, and Foster Wheeler-Stoic gasifiers are currently marketed in the United States. Operation and control of these units are similar to each other. Only Woodall-Duckham offers an oxygen-blown system for production of medium-Btu gas.

Woodall-Duckham Gasifier.[7] The Woodall-Duckham gasifier consists of a refractory-lined drying and devolatilization (or retort) section atop a water-jacketed gasification and combustion section (Figure 18). Sized coal is introduced into the gasifier through a lockhopper system controlled by the solids level of the devolatilization section. Air (or oxygen) and steam are distributed at the bottom through a rotating grate that also removes ash to the twin ash hoppers.

[7] Gilbert/Commonwealth Co.

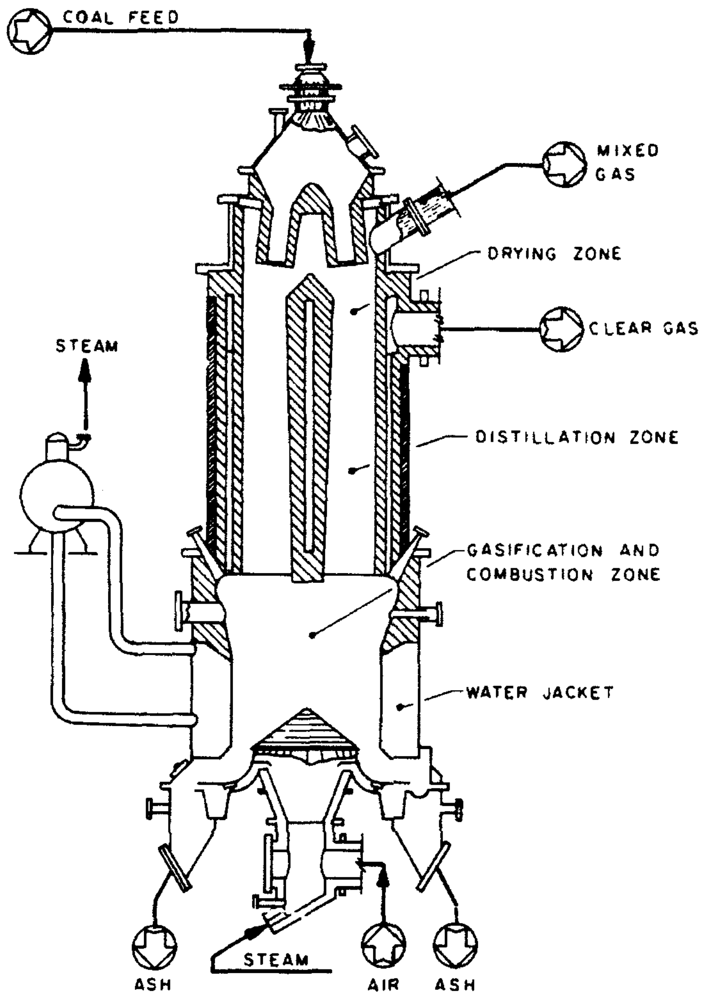

Figure 18. Woodall-Duckham gasifier.

Two sizes of gasifiers are available. A 10-ft-diameter unit, which can handle 3 to 3.5 tons/hr of feed coal, has a 17-ft-high retort and an 8-ft-high water-jacketed section, respectively. The 12-ft-diameter unit can handle 3.5 to 4.5 tons/hr of coal feed. The general characteristics and requirements of coal feed, along with a typical proximate analysis of bituminous coal, are summarized in Table 12.

In an air-blown operation, 2.3 lb air/lb coal and 0.25 lb steam/lb coal are required. The blast saturation temperature of the steam-air mixture is about 130 °F. Depending on the coal's ash fusion temperature, the steam/air ratio can be regulated to maintain the gasification/combustion zone temperature in the range of 2000 to 2500 °F. The top gas temperature is normally regulated in the range of 220 to 250 °F and the bottom gas is kept in the range of 900 to 1500 °F. The operating pressure is maintained at about 40 in. of water at the gasifier outlet. The gasifier can be turned down to about 30 percent of design capacity.

To produce a hot raw gas, the top gas is passed through a tar cyclone to remove large droplets of tar and the bottom gas flows through a dust cyclone to remove entrained dust. The gases are then combined where the heat in the bottom gas revaporizes the tar/oil mists entrained in the top gas. The hot raw gas at a temperature of about 700 °F can be distributed in unlined but insulated mains up to 1500 ft without condensation. The thermal efficiency is approximately 88 to 92 percent. The effective heating value of the hot raw gas is 200 to 210 Btu/SCF including sensible heat and the heating value of the tar and oil.

Table 12

Coal Feed Characteristics for Woodall-Duckham Two-Stage Gasifier

Size	• Must be faily uniform; typical size range: 3/8" to 1", 1/2" to 1-1/2", or 3/4" to 2" • Can accept only a limited quantity of fines
FSI	• Less than 1-1/2" ideally, but could use coals with FSI up to 2-1/2" or 3"
Ash Fusion Point	• Greater than 2000 °F ideally, but may be as low as 2050 °F
Typical Bituminous Coals	
Proximate Analysis, %	3.02
Moisture	31.96
Volatile matter	56.64
Fixed Carbon	8.38
Total	100.00
Sulfur content (dry, wt %)	3.89
HHV, Btu/lb	13,000
Feed Rate, TPD	72 - 84 for 10-ft-dia unit

Alternatively, tar droplets are first separated from the top gas in a tar precipitator operated above the gas dewpoint. The detarred gas is then cooled and passed through a second precipitator to remove oil and water. This gas mixes with the dedusted, cooled bottom gas and forms the cold clean gas. The cold clean gas has a heating value of about 176 Btu/SCF at 120 °F. The thermal efficiency is about 75 percent. The cold clean gas can be desulfurized in a standard sulfur removal unit such as Stretford, if necessary. The schematic process flow diagrams for hot raw gas and cold clean gas are shown in Figures 19 and 20, respectively. Medium-Btu gas can be produced by substituting oxygen for air or by cyclic operation with air and superheated steam. Table 13 summarizes the compositions and characteristics of typical product gas.

Two operators are normally sufficient to operate a plant with two gasifiers, dust and tar/oil removal equipment, as well as a desulfurization unit. Annual shutdown is normally required for regular maintenance. The gasifier refractory usually lasts more than 10 years without major rebuilding. The rotating grate lasts 3 to 10 years. The grate is constructed of segments; therefore only individual segments may need to be replaced during maintenance.

Medium-Btu gases can be generated from the Woodall-Duckham gasifier by substituting oxygen for air or by cyclic operation. The cyclic operation consists of heating the carbon bed to incandescence with air, then shutting off the air and blowing steam through the bed. Steam reacts with carbon at high temperatures to form carbon monoxide and hydrogen. The product gases, sometimes called "blue water" gas, have a heating value of approximately 300 Btu/SCF. The steam carbon reaction is highly endothermic, causing a rapid temperature drop and decreased gasification rate within the carbon bed. The steam is then shut off and air flow reestablished to reheat the bed. A medium-Btu gas is thus produced by cycling the flow of air and steam through a carbon bed.

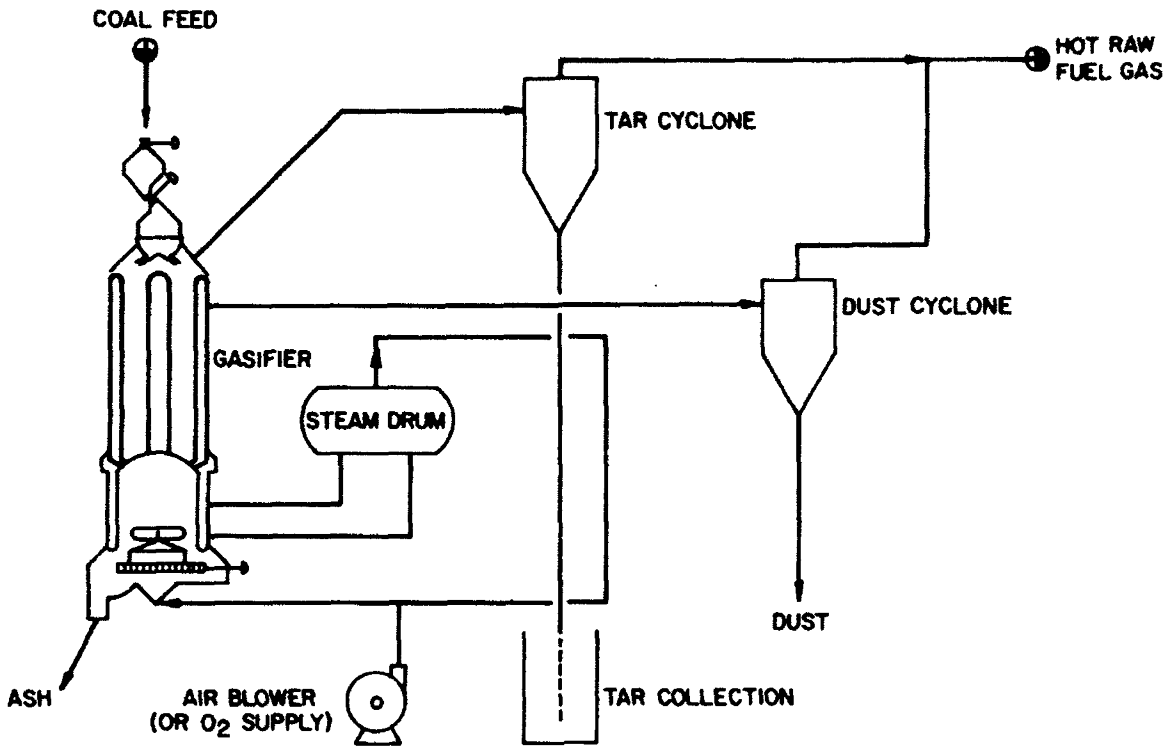

Figure 19. Woodall-Duckham process for hot raw gas.

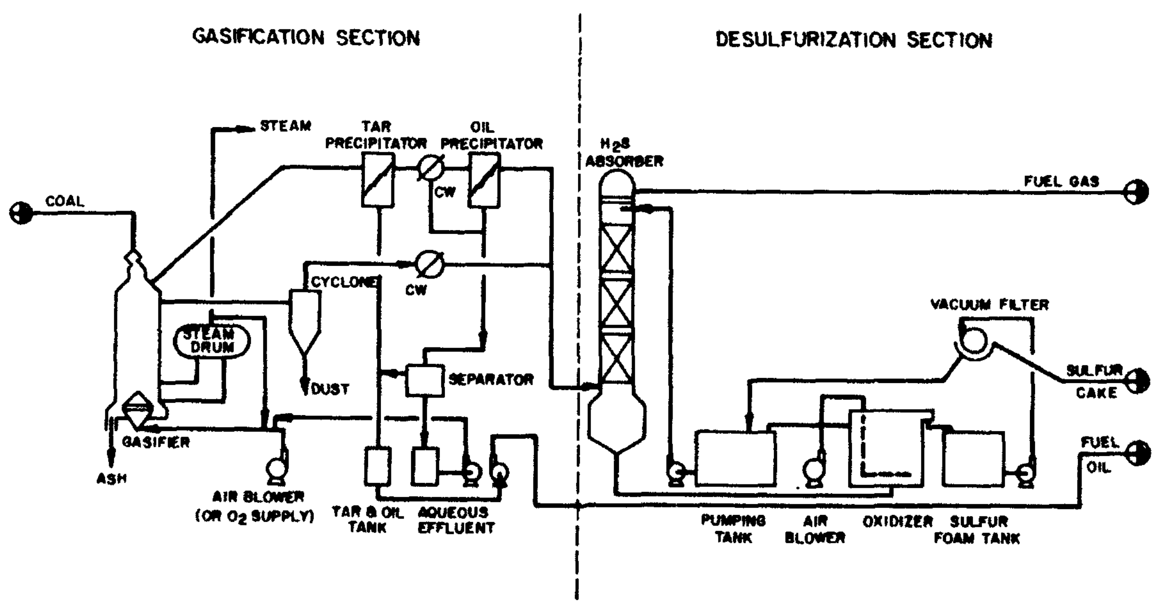

Figure 20. Woodall-Duckham process for desulfurized cold clean gas.

Table 13

Product Gas Types Available From Woodall-Duckham Two-Stage Process

	Med.-Btu Gas		Low-Btu Gas	
	Cyclic	O_2-Blown	Hot Raw	Cold Clean
Composition, male % (moisture, tar, tar oil free)				
H_2	52.2	38.4	17.0	17.0
CO	28.5	37.5	28.2	28.2
CO_2	8.0	18.0	4.5	4.5
CH_4	6.5	3.5	2.7	2.7
N_2	4.2	2.2	47.1	47.1
Others (H_2S, COS, NH_3)	0.6	0.4	0.5	0.5
Total	100.0	100.0	100.0	100.0
Tar and Tar Oil, lb/lb coal	Not Available	Not Available	0.075-0.12	—
Temperature, °F	—	—	600-700	120
Sp. gr. (Air = 1)	0.52	0.73	—	0.83
Wobbe No. (a)	465	334	—	193
Thermal efficiency, %	—	89-93	88-92	74-76
Gas prod. rate, SCF/lb coal	—	—	—	50-53

(a) Higher heating value of gas divided by the square root of the gas specific gravity.

The Woodall-Duckham gasifier has been in commercial use as a cyclic medium-Btu gas generator since the 1920s and as a continuous air-blown fuel gas generator since 1942. Table 14 is a partial listing of Woodall-Duckham gasifiers used to produce industrial fuel gas. Synthesis gas or public utility gas can be produced by cyclic or oxygen-blown operations. Tables 15 and 16 list the utility gas and synthesis gas plants built since 1946. None of these units are currently in operation.

ATC/Wellman-Incandescent Gasifier.[8] Coal is fed from the bunker through an automatic drum feeder to the top of the distillation retort (Figure 21). The feeder is controlled by the solids level in the retort. Fresh coal is dried and devolatilized slowly by the ascending top gas. The coal is converted to semicoke by the time it descends to the gasification zone. Most of the hot gas produced in the gasification zone exits through the bottom gas offtake. At the bottom of the gasifier, stationary plows remove ash from a rotating grate through a water seal and into an ash pan. The air and steam mixture entering at the base of the gasifier is distributed across the bed by the grate. The gasification and combustion sections of the gasifier are water-jacketed and provide part of the steam required for gasification.

Table 17 summarizes properties of typical coal feed. Nominal coal feed rate, thermal output, and thermal efficiency for various standard size gasifiers are given in Table 18. For the ATC/Wellman-Incandescent gasifier, 2.5 lb air and 0.32 lb steam/lb coal are required for air-blown operation. A steam/air ratio of 0.13 is used to produce a BST of 134 °F. The operating pressure of the gasifier is atmospheric. The unit can be turned down to about 25 percent of its design capacity and can be brought back to full production within 20 min.

[8] Gilbert-Connonwealth Co.; G.E. Brewer and C.K. Moore, "Economic Evaluation of the ATC/Wellman Incandescent Two-Stage Low-Btu Coal Gas Producer," paper presented at the Coal Technology Conference, Houston, TX (October 1978).

Table 14

Commercial Experience for Woodall-Duckham Gasifier (Industrial Fuel Gas Plants)

Company/Location	No. of Units	Gasifier Diameter, ft	Type	Status
Weldless Steel Tube Co. Wedensfield, England	2	10	Bituminous	Non-Operational
Ziar Aluminum Works Czechoslovakia	7	10	Bituminous	Non-Operational
Chomutov Tube Works Czechoslovakia	14	10	Lignite	Operational
Istanbul Gas Utility Turkey	1	8.5	Lignite	Operational
Australian Consolidated Industries, Ltd. Sydney, Australia	4	10	Bituminous	Non-Operational
Melbourne Gas Works Melbourne, Australia	2	10	Bituminous Brown	Non-Operational
Elgin Fireclay Ltd. Springs, South Africa	1	8.5	Bituminous	Operational
Vaal Potteries Ltd. Meyerton, South Africa	1	8.5	Bituminous	Operational
Union Steel Corporation Johannesburg, South Africa	2	10	Bituminous	Operational
Stewarts & Lloyds Steelworks, South Africa	3	10	Bituminous	Operational
Masonite, Escault South Africa	3	10	Bituminous	Operational
SAAPI, Mandini, South Africa	2	10	Bituminous	Operational
Rand Water Board, Vereeniging, South Africa	1	8.5	Bituminous	Operational
Driefontein, Carltonville, South Africa	2	10	Bituminous	Operational
Vereeniging Refractories South Africa	2	10	Bituminous	Operational

Table 15

Commercial Experience for Woodall-Duckham Gasifier (Public Utility Gas Plants)

Company/Location	No. of Units	Gasifier Diameter, ft
St. Poelten, Austria	2	6
Rome, Italy	5	8.5
Trieste, Italy	2	10
Como, Italy	1	6
Genoa, Italy	4	12
Vierzon, France	2	8.5
Kensal Green, England	1	10
Ulm, West Germany	2	8.5
Zagabria, Yugoslavia	1	6
Prague, Czechoslovakia	6	8.5
Warsaw, Poland	3	12
Posen, Poland	3	10
Thom, Poland	2	6
Tokyo, Japan	5	12

Table 16

Commercial Experience for Woodall-Duckham Gasifier (Synthesis and Water Gas Plants)

Company/ Location	No. of Units	Gasifier Diameter, ft	Coal Type	Scope of System
OSW Fertilizer Plant Linz, Austria	4	8.5	Unknown	Med-Btu Gas
Vetrocoke, Porto Marghera, Italy	2	6	Bituminous	Med-Btu Cyclic Gas (a)
Montecatini, Croton, Italy	2	8.5	Unknown	Med-Btu Gas
Montecatini, St. Giuseppe di Cairo, Italy	2	10	Unknown	Med-Btu
I.M.A.D., Naples, Italy	2	6	Bituminous	Med-Btu Cyclic Gas
State Works, Semtin, Czechoslovakia	4	6	Coke (b)	Med-Btu Cyclic Gas
D. Swarovski Co., Wattens, Austria	2	6	Coke (b)	Med-Btu Cyclic Gas
Edison S.P.A. Milan, Italy	1	10	Coke (b)	Med-Btu Cyclic Gas
Marconi S.P.A., Aquila, Italy	1	6	Coke (b)	Med-Btu Cyclic Gas
Public Utility, Paris, France	3	14	Coke (b)	Med-Btu Cyclic Gas
Public Utility, Fuerth, West Germany	1	6	Coke (b)	Med-Btu Cyclic Gas

(a) Cyclic gas by alternate blasting of superheated steam and air separately.
(b) When coke is used as feed, the top retort zone is not required and the gasifier in reality becomes a single-stage system.

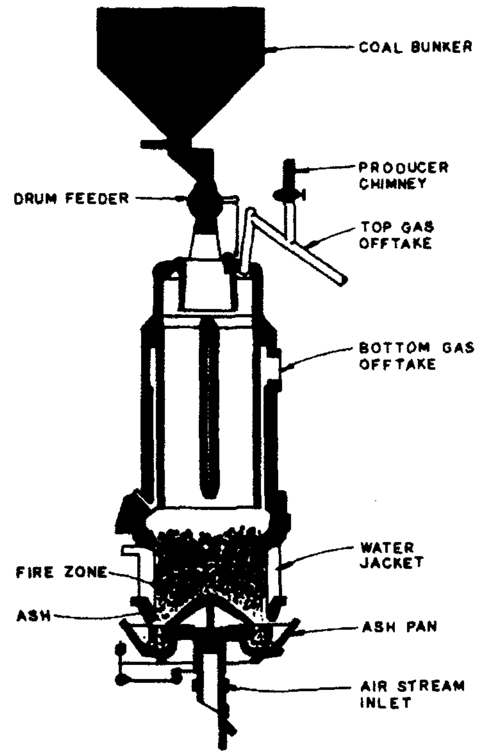

Figure 21. ATC/Wellman-Incandescent two-stage coal gasifier.

Table 17

Desirable Feed Coal Properties for ATC/Wellman-Incandescent Gasifier

Free Swelling Index	1 to 3
Ash Fusion Temperature	greater than 2200 °F
Coal Size	2" to 3", 1-1/2" to 2-1/2", or 3/4" to 1-1/2"
Allowable Undersize	
Max. 10% by wt.	5/16" to 2"
Max. 15% by wt.	fines less than 5/16"
Max. Moisture Content	15 wt %
Hardgrove Index	40 to 70
Typical Bituminous Coal	
Moisture	4.65%
Volatile Matter	34.24
Fixed Carbon	52.33
Ash	8.78
	100.00%
HHV	12,470 Btu/lb
Sulfur Content	3.87%

Table 18

Coal Feed Rate, Thermal Output Rate, and Efficiency on Wellman-Incandescent Two-Stage Gasifiers

		Thermal Output, 10^9 Btu/day			Thermal Efficiency, % (a)		
Gasifier Diameter, Feet	Coal Feed Rate, TPD	Hot Raw Gas	Hot Detarred Gas	Cold Clean Gas	Hot Raw Gas	Hot Detarred Gas	Cold Clean Gas
4.50	13.92	0.30	0.28	0.25	89.8	83.3	76.2
5.50	20.40	0.44	0.41	0.37	90.2	83.8	76.0
6.50	29.40	0.64	0.59	0.54	90.1	84.0	75.9
8.50	51.90	1.12	1.05	0.95	90.2	84.0	75.9
10.00	71.40	1.54	1.45	1.30	90.1	84.9	76.1
10.75	82.56	1.79	1.67	1.51	90.5	84.3	76.3
12.00	103.20	2.23	2.08	1.88	90.1	84.0	76.0

(a) Based on 12,000 Btu/lb coal.

The process flow scheme for production of hot raw gas is shown in Figure 22. Large droplets of tar are removed from the top gas (240 °F) in a tar cyclone without cooling. The bottom gas (1170 °F) is dedusted in a separate cyclone. These two gases combine to form the hot raw gas (690 °F). This gas has an effective heating value of 200 Btu/SCF which includes the heating value of the tar/oil and the sensible heat. The hot gas thermal efficiency of this process is about 90 to 93 percent. Alternatively, the top gas from the tar cyclone passes through an electrostatic tar precipitator operated above the gas dewpoint to remove all tar mist (Figure 23). The detarred top gas then mixes with the separately dedusted bottom gas to form the hot detarred gas. The thermal efficiency of this scheme is about 84 percent and the heating value of the gas is about 185 Btu/SCF. To produce a cold clean gas, the top gas is first passed through a hydraulic seal to remove the large tar droplets (Figure 24). It then flows to an electrostatic precipitator operated above the gas dewpoint to remove the fine tar mists. The bottom gas is quenched directly in a spray column. Both gases are then mixed in an indirect tubular cooler and then move to a second precipitator for oil removal. The cold clean gas exits the deoiler at a temperature of about 120 °F with a heating value of 175 Btu/SCF. The thermal efficiency for cold clean gas production drops to about 76 percent. Table 19 lists typical gas compositions for a hot raw gas arrangement using bituminous coal feed.

Commercial application of the ATC/Wellman-Incandescent gasifier is largely confined to South Africa. Table 20 lists the commercial gasifiers that have been installed since 1964.

Foster Wheeler-Stoic Gasifier.[9] Sized coal is fed by a rotary feeder to the top of the gasifier. The upper section of the gasifier is refractory-lined and the lower section is water-jacketed. To avoid solids bridging and to allow for swelling of raw coal tar, the upper retort section is divided into equally sized segments and is tapered outward toward the bottom. Constant solids level in the retort is maintained automatically. Wet ash is removed from the bottom of the gasifier through a water-sealed ash pan that rotates with the grate. The steam-air mixture is introduced at the bottom of the gasifier and distributed through the rotating grate. Most of the steam required for gasification is generated in the gasifier's water jacket.

[9] Gilbert/Commonwealth Co.; W.W. Bodle and J. Huebler; R.P. Lewis and W.E. Soderberg, *Gasifier in Industry Program, University of Minnesota-Duluth Campus, Gasifier Final Project* Report, Report No. DOC/ET/10188-1410 (DOE, January 1984).

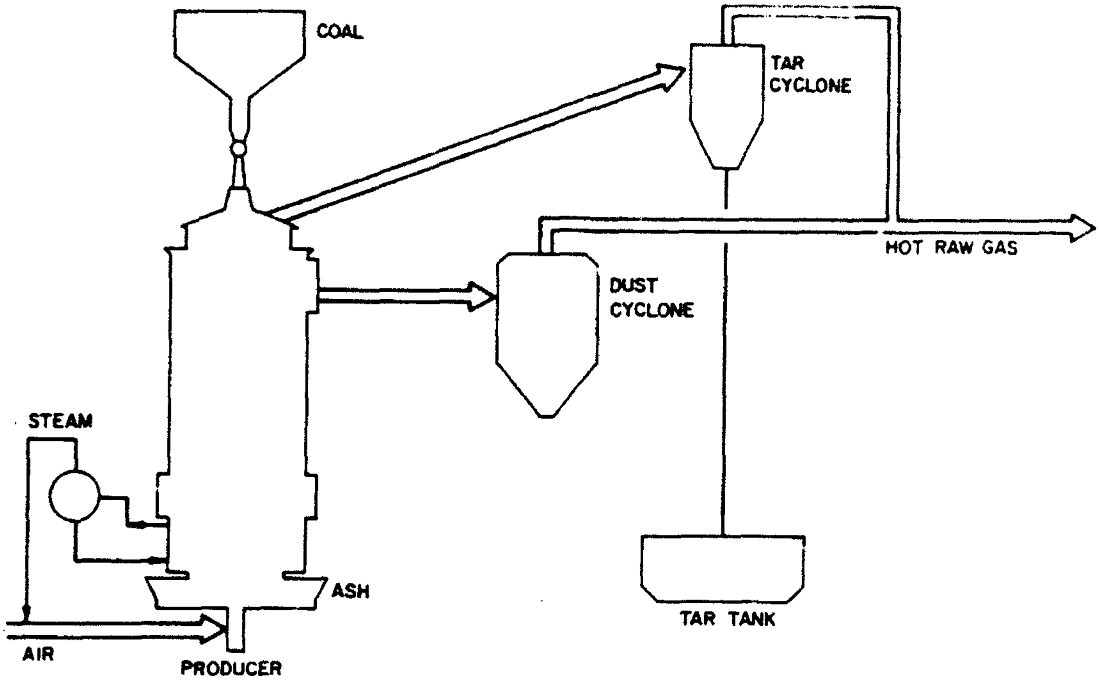

Figure 22. ATC/Wellman-Incandescent hot raw gas producer.

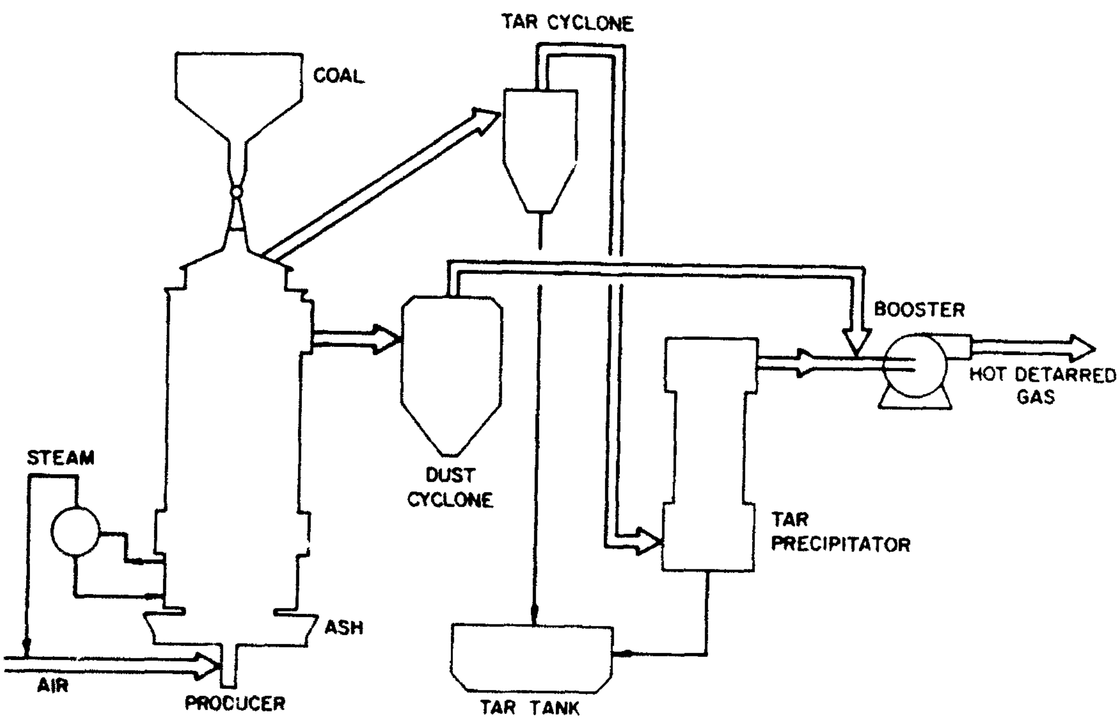

Figure 23. ATC/Wellman-Incandescent hot detarred gas producer.

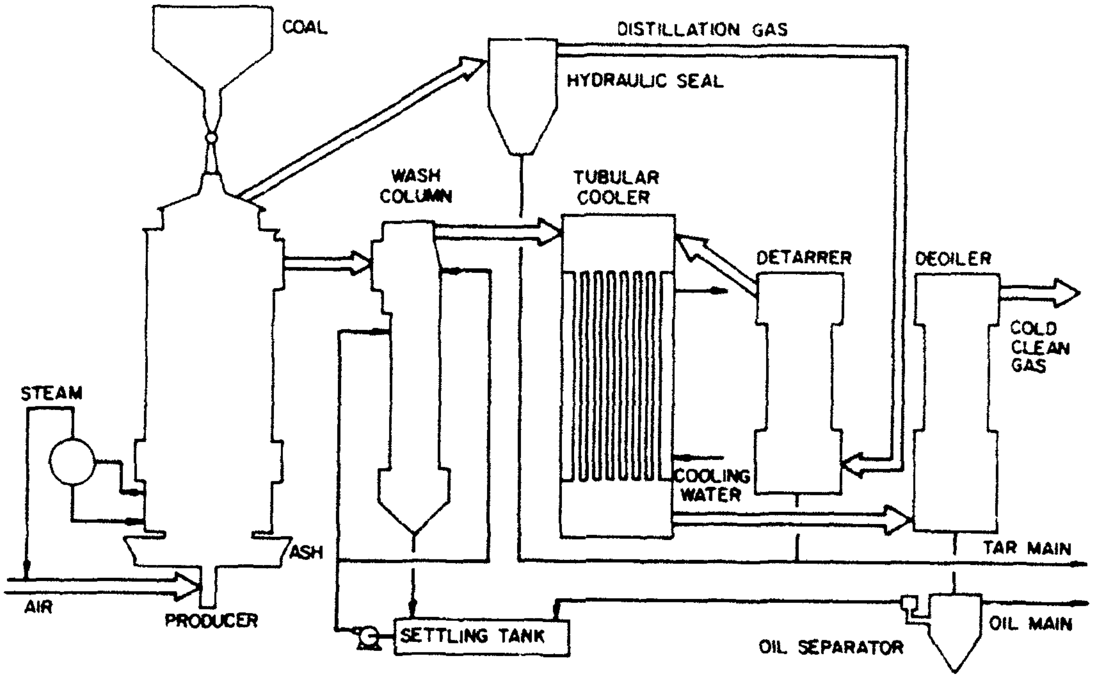

Figure 24. ATC/Wellman-Incandescent cold clean gas producer.

Table 19

Typical Gas Conditions for Hot Raw Gas Arrangement

Volume %	Top	Bottom	Combined
H_2	19.50	12.25	60.0
CO	30.00	29.50	29.75
CH4	4.80	0.85	2.89
C_2H_4	0.40	0.25	0.33
CO_2	2.45	4.20	3.30
O_2	0.35	0.55	0.45
N_2	42.50	52.40	47.28
*H_2S ppmv	N/A	N/A	3200
Tar lb/SCF	0.00398	—	0.0012
Oil lb/SCF	0.0012	—	0.00036
Dust lb/SCF	—	Traces	Traces
Temp. °F	240	1200	912
Relative Flow	0.30	0.70	1.0

* Based on a bituminous coal containing 2 wt % sulfur.

Table 20

Commercial Experience for Wellman-Incandescent Gasifier

Plant Owner (a)	No. of Operating Gasifiers	Gasifier Diameter, (Feet)	Heat Rate, 10^9 Btu/Day	Coal Type	Scope of System (b)	Application	Status (c)
SCAW Metals, Ltd.	1	10.00	0.7	Bituminous	Single Stage	Rolling Mill and Miscellaneous	1963
Stewarts & Lloyds	1	8.50	1.0	Bituminous	Two-Stage Hot Raw	Miscellaneous Furnaces	1964
Cullinan Refractories	2	6.50	0.6	Bituminous	Two-Stage Hot Raw	Tunnel Kilns	1964
Cullinan Refractories	1	8.50	1.0	Bituminous	Two-Stage Hot Raw	Basic Refractory Kilns	1965
Union Steel Corp.	4	10.00	4.8	Bituminous	Two-Stage (Three Hot Raw) (One Cold Clean)	Steel Making Furnaces and Miscellaneous	1965
Southern Cross Steel	1	10.00	1.2	Bituminous	Two-Stage Cold Clean	Stainless Steel Reheating and Heat Treatment Furnaces	1966
Consolidated Class	2	10.00	2.7	Bituminous	Two-Stage Hot Raw	Glass Making Furnace	1967
Union Steel Corp.	1	10.00	0.7	Anthracite	Single Stage	Steel Making Furnaces and Miscellaneous	1968
SCAW Metals, Ltd.	2	10.75	2.6	Bituminous	Two-Stage (One Cold Clean) (One Hot Detarred)	Rolling Mill and Miscellaneous	1968
Highveld Steel	4	10.00	5.4	Bituminous	Two-Stage Cold Clean	Rolling Mill Furnaces	1968
Lurgi, Groolfontein	1	6.50	0.6	Bituminous	Two-Stage Hot Raw	Rotary Zinc Kiln	1970
SCAW Metals, Ltd.	1	10.75	1.5	Bituminous	Two-Stage Hot Detarred	Rolling Mill and Miscellaneous	1970
Cullinan Refractories	1	8.50	1.0	Bituminous	Two-Stage Hot Raw	Refractory Brick Kilns	1973
SAICCOR	1	10.00	1.2	Bituminous	Two-Stage Cold Clean	Pulp and Paper Drying	1973
Johannesburg Consolidated Inv. Co.	1	6.50	0.66	Bituminous	Two-Stage Hot Raw	Antimony Concentrate	1975
SCAW Metals, Ltd.	1	10.75	1.5	Bituminous	Two-Stage Hot Detarred	Steelworks, Reheat Annealing Furnaces, etc.	1975
Southern Cross Steel	1	10.00	1.2	Bituminous	Two-Stage Cold Clean	Stainless Steel Reheat Furnaces, etc.	1976
Highveld Steel	2	10.00	2.3	Bitumionus	Two-Stage Cold Clean	Steel Mill Reheat Furnaces	1976
Caterpillar Tractor Co., York, PA	1	10.00	2.5	Bituminous	Two-Stage Cold Clean	Heat Tracing	1978
Land O'Lakes, Minnesota	1	10.00	1.3	Bituminous	Two-Stage Hot Raw	Boilers and Whey Drying	1979

(a) All plants are located in South Africa, except Caterpillar Tractor Co. and Land O'Lakes.
(b) All products are low-Btu gas.
(c) Year completed.

Raw coal is typically sized to 1/2 to 1-1/2 in. or 1-1/2 to 3 in. The FSI of coal feed is normally below 3 with an ash-fusion temperature preferably greater than 2200 °F. The typical characteristics of coal feed are given in Table 21. Currently, the gasifier is available in four sizes: 6.5, 8.5, 10.0, and 12.5 ft inside diameter. The 6.5-ft-diameter unit handles about 1.3 tons/hr of coal and the 12.5-ft-diameter unit can process about 4.5 tons/hr. The individual gasifier can be turned down to 20 percent of the design capacity. This turndown ratio can be substantially increased with multiple-train operation.

To produce the hot raw gas, the top gas (250 °F) is first passed through a hot cyclone to remove the large droplets of tar/oil. It then combines with the dedusted bottom gas that leaves the gasification zone at about 1200 °F. The resulting hot raw gas mixture has a heating value of 186 to 207 Btu/SCF. The thermal efficiency is 85 to 93 percent. To produce a hot detarred gas (175 to 195 Btu/SCF), additional tar/oil is removed by an electrostatic precipitator instead of the tar cyclone (Figure 25). The thermal efficiency for this scheme is 77 to 87 percent. The third mode of operation produces a cold clean gas having a heating value of 160 to 175 Btu/SCF and a thermal efficiency of 69 to 76 percent. In this mode, the bottom and top gas streams are water-cooled to remove all condensibles. Table 22 lists typical ranges of gas compositions for a hot detarred gas and the properties of a typical tar/oil produced by this process.

Foster Wheeler Energy Corp. acquired the design of the two-stage Stoic gasifier from Stoic Combustion Pty., Ltd. of Johannesburg, South Africa. Stoic has 30 commercial installations around the world, with one in South Africa operating longer than 30 years.

The first commercial-scale installation in the United States is located at the University of Minnesota-Duluth. The project was part of the U.S. Department of Energy (DOE) Gasifiers in Industry Program. A 10-ft-diameter, 3 ton/hr Foster Wheeler-Stoic two-stage gasifier was installed and operated to provide low-Btu gas and byproduct tar/oil for boilers that were burning natural gas and fuel oil. The primary objective of the program was to evaluate the fixed-bed gasifier in an actual operating environment. In addition, environmental and occupational health data were obtained. The project began in 1976 and ended in 1982. The gasifier ran with subbituminous coals having a thermal efficiency range of 87 to 95 percent. The product gas was burned with no problems in the boilers and no boiler flue gas emission control equipment was needed. The boiler thermal efficiency on low-Btu gas was not significantly different than with natural gas.

Economic Analysis

The economics of fixed-bed coal gasification plants can be evaluated by using cash flow analysis techniques. The software model used for this part of the study is a fairly standard type of financial analysis software that incorporates all initial capital costs as well as annually recurring costs. The model includes inputs for: (1) capital structure (50 percent debt/equity financing), (2) the cost of debt and equity (9 percent and 12 percent, respectively), and (3) plant life (20 years). In addition, the model will calculate the Interest During Construction based on the construction time (1 year) and interest rate (10 percent), using a nonutility method of financing construction interest. The analysis considers the repayment of initial funding sources through the establishment of debt and equity sinking funds. These funds providerepayment of debt and equity principal, whereas a separate fund accounts for payment of debt interest and equity dividends. Provisions for taxes and straight-line depreciation are also included. The depreciation uses a 20-year life that corresponds with the project life used in the analysis. The analysis as performed here applies only to cases involving private forms of financing.

The primary output is the levelized cost of service, which is a financially weighted average service cost over the life of the equipment given in dollars per unit of output (million Btus). In most cases, including the fixed-bed gasifier plant, the cost of service will decrease over time. The levelized costs of

Table 21

Typical Coal Feed Characteristics of Foster Wheeler-Stoic Gasifier

Size		• Must be fairly uniform • 3/4" to 1-1/2" or 1-1/2" to 3" • Can accept limited quantity of fines
FSI		• Up to 3
Ash Fusion Temperature		• Greater than 2200 °F
Type		• Subbituminous, lignite, bituminous
Typical Bituminous Coal, wt %		
Moisture	9.2	
Volatile Matter	36.7	
Fixed Carbon	43.8	
Ash	10.3	
Total	100.0	
Sulfur, wt %	3.2	
HHV, Btu/lb	12,000	

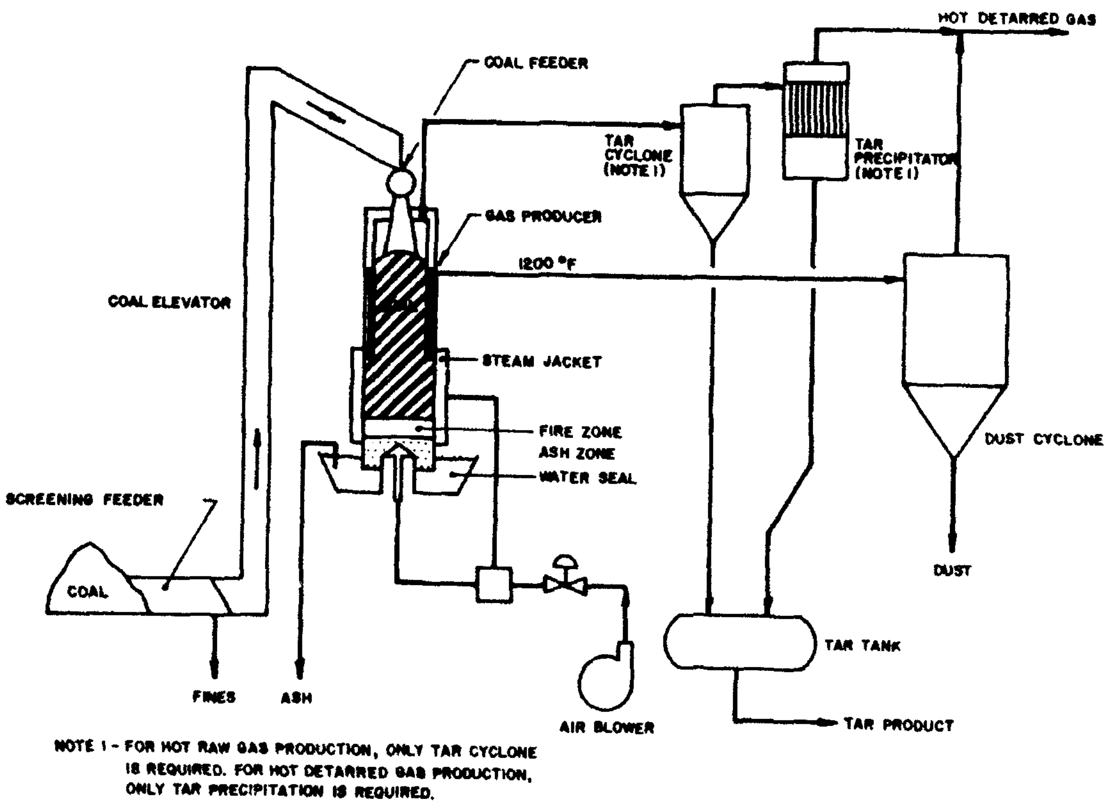

Figure 25. Foster Wheeler-Stoic process for hot detarred gas.

Table 22

Analysis of Hot Detarred Gas and Typical Tar Oil (Foster Wheeler-Stoic)

Analysis of Detarred Gas	
Component	%
H_2	14.0-16.0
CH_2	2.6-3.0
CO	29.0-30.0
CO_2	3.0-4.0
N_2	47.6-51.4
Analysis of Tar-Oil	
Parameters	Physical Property
Specific Gravity	1.0355
Viscosity, Centistokes, 122 °F	555.4
Viscosity, Centistokes, 210 °F	21.35
Pour Point, °F	80
Flash Point, C.O.C., °F	315
Higher Heating Value, Btu/gal	148,265
Chemical Composition	
Component	%
Carbon	85.92
Hydrogen	7.92
Oxygen	4.18
Nitrogen	1.05
Sulfur	0.22
Ash	0.11
Moisture	0.68
Total	100.00

service for different projects can be compared to determine the most economically attractive options. In addition, sensitivity studies can be performed to measure the impact of changes in important variables such as capital costs, coal costs, and plant capacity while holding all other variables constant.

A fixed-bed coal gasification plant with a nominal production capacity of 6 x 10^9 Btu/day of low-Btu gas was selected as the base plant for economic analysis. The product gas is combusted in an existing DOD boiler plant to generate approximately 200,000 lb/hr of steam. The generalized process block flow diagrams using single- and two-stage gasifiers are shown in Figures 26 and 27, respectively. The product gas is utilized in one of three forms:

- Hot raw gas (Case A)
- Cold clean gas without sulfur removal (Case B)
- Cold clean gas with sulfur removal (Case C).

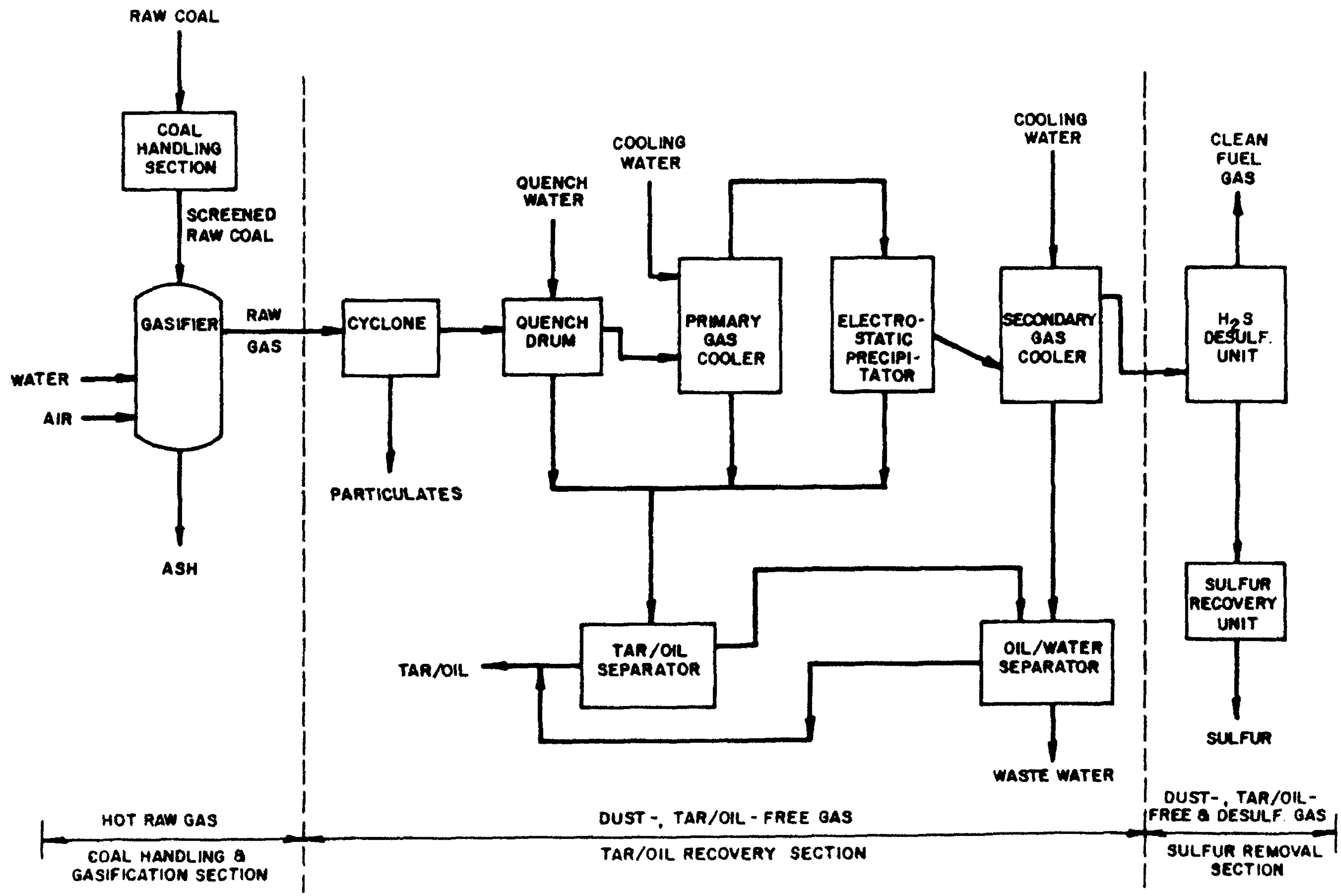

Figure 26. Single-stage fixed-bed coal gasification process.

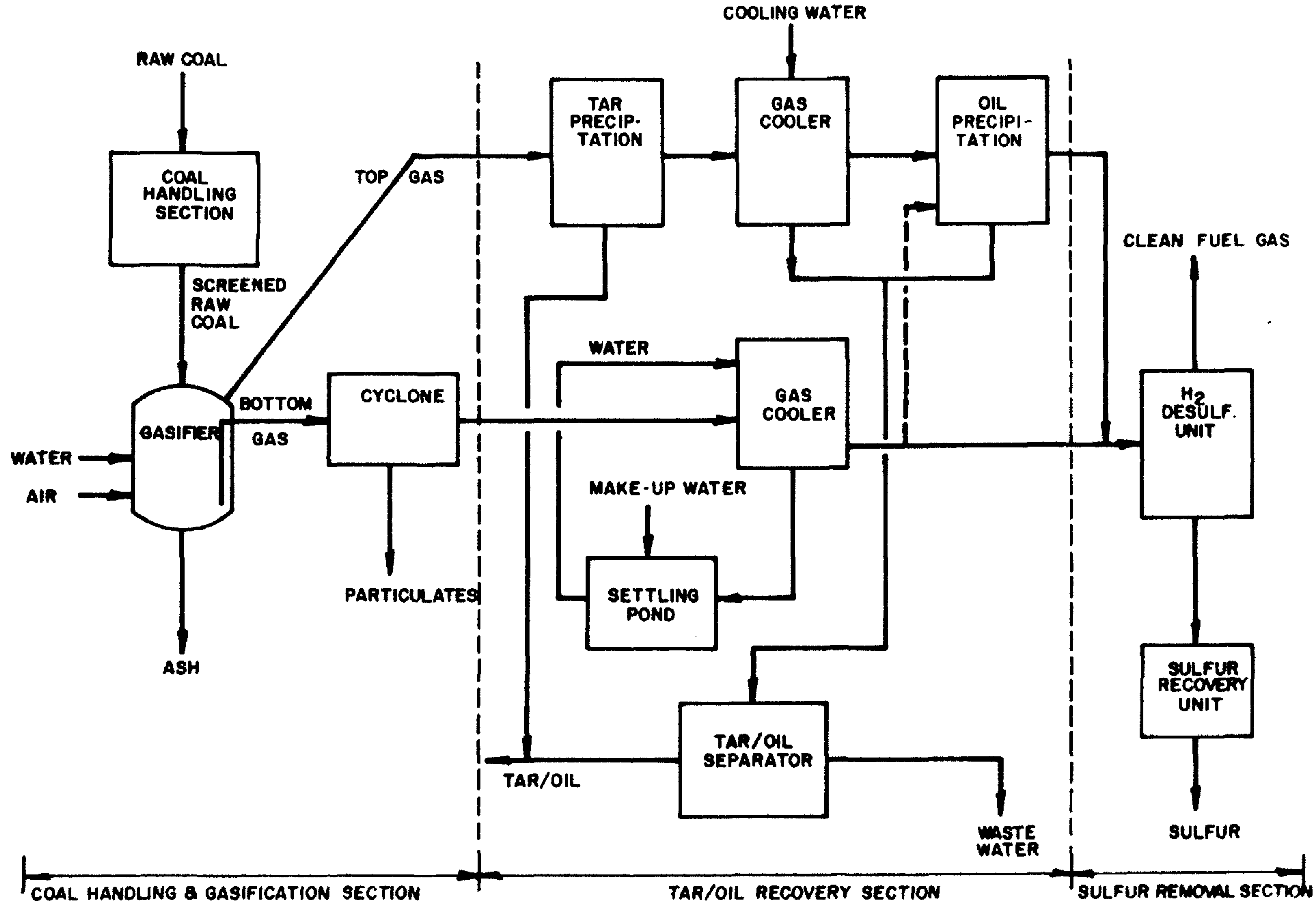

Figure 27. Two-stage fixed-bed coal gasification process.

The process design conditions for the above cases are summarized in Table 23, and the coal feed characteristics are given in Table 24. The initial capital costs and annual operating costs are presented in Tables 25 and 26, respectively. The onsite facilities construction investments of the capital cost were averaged from the equipment costs of three single-stage and two two-stage 2.5 x 10^9 Btu/day fixed-bed coal gasification plants as published in a 1977 cost study.[10] A capacity exponent of 0.6 on the plant capacity ratio was used for scale-up. The equipment costs were then adjusted for inflation using Chemical Engineering's M&S Equipment Cost Index. The levelized costs of the product gas, along with the capital and operating costs, are presented in Table 27.

Figures 28 through 30 depict the sensitivity of product gas cost (cost of service) to variations in capital costs, coal cost, and plant capacity, respectively. The product gas cost is more sensitive to changes in coal cost than in capital costs. A 15 percent increase in coal cost produces a 35¢/MBtu increase in product cost whereas the same magnitude change in capital costs only produce a 10¢/MBtu increase. The product cost decreases substantially as the plant output increases and levels off approximately at the base-case output of 1.97 x 10^{12} Btu/yr. This leveling-off effect can be attributed to the increasing importance of operating cost—especially the raw material costs—compared with the capital costs when plant output increases.

Commercial Fluidized-Bed Gasifiers

In a fluidized-bed gasifier, sized coal particles (typically 3/8 x 0 in.) are suspended by the rising current of reactant gases. Gas superficial velocities range from 0.5 to 1.5 ft/sec. Although the bed of solids is stationary as a whole, the coal particles themselves are in an extreme state of agitation. Fluidized beds of solids are characterized by their resemblance to a boiling liquid and by their lack of thermal and concentration gradients caused by extreme turbulence and backmixing within the bed. Fluidized-bed technology has been applied successfully in many chemical operations such as the catalytic cracking of petroleum fractions.

Fluidized-bed gasifiers normally operate at a higher temperature than fixed-bed units. Complete mixing of the gas and solids within the bed results in a higher outlet-gas temperature. This condition reduces the thermal efficiency of the gasifier, but also minimizes the production of tars and oils, consequently reducing raw gas cleanup needs. The high gas superficial velocities may cause excessive carryover of fine particles with high carbon content in the outlet gas which can lower the overall carbon conversion. Therefore, the elutriated fines must be either collected outside the gasifier and used as boiler fuel or reinjected into the gasifier and reconverted to avoid economic losses.

As coal is gasified, the physical and chemical characteristics of the residual particles such as size, density, and chemical properties also change. As the gasification reactions advance, the hydrocarbon fractions of coal disappear and the denser mineral fraction remains in the bed. The mineral content buildup in the gasifier bed must be balanced by a steady removal of the residual ash material; otherwise, the gasification rate and fluidization behavior of bed solids can be severely affected.

Fluidized-bed gasifiers generally cannot directly handle highly caking coals without an oxidative pretreatment step. Raw coal is heated to reactor temperature almost instantaneously in a fluidized-bed gasifier. Pyrolysis and steam-coal reactions are too slow to maintain the thermal pace; hence, the particles melt and, upon touching other melted particles, agglomerate to form large particles, or clinkers. This condition results in defluidization or collapse of the bed, and ultimately an inoperable system.

[10] Gilbert/Commonwealth Co.

Table 23

Process Design Conditions for a Fixed-Bed Coal Gasification Plant

Plant Capacity, Btu/day	6×10^9 Case A	Case B	Case C
Type of Product Gas	Hot Raw Gas	Cold Clean Gas Without Sulfur Removal	Cold Clean Gas With Sulfur Removal
Coal, Throughput, TPD	251.5	301.7	325.0
By-Product			
Tar, GPD	-	4,799.6	5,167.0
Sulfur, TPD	-	-	8.28
Sulfur Removal Process	-	-	Stretford
Thermal Efficiency, %	91.8	76.0	74.0

Table 24

Characteristics of Coal Feed for a 6×10^9 Btu/Day Fixed-Bed Coal Gasification Plant

	Low Sulfur Coal (Stockton, WV)	High Sulfur Coal (Belmont, OH)
Proximate Analysis, wt %		
Moisture	3.0	4.0
Volatile Matter	34.9	38.3
Fixed Carbon	54.3	47.0
Ash	7.8	10.7
	100.0	100.0
Ultimate Analysis, wt %		
Hydrogen	5.2	5.2
Carbon	75.4	69.4
Nitrogen	1.4	1.5
Oxygen	9.6	9.9
Sulfur	0.6	3.3
Ash	7.8	10.7
	100.0	100.0
Heating Value, as received, Btu/lb	13,480	12,600
Ash Softening Temp., °F	2910	2080
FSI	5.5	4.5

Table 25

Initial Capital Costs for a 6 x 10^9 Btu/Day Fixed-Bed Coal Gasification Plant

(Units in Millions of Dollars, 4th Quarter, 1986)

	Case A	Case B	Case C
	Hot Raw Gas	Cold Clean Gas Witho it Sulfur Removal	Cold Clean Gas With Sulfur Removal
Facilities Construction Investment (FCI) Onsite and Offsite Facilities	5.916	8.519	12.274
Project Contingency 15% of FCI	0.887	1.263	1.841
Contractor Overhead & Profit 6% of TFCI	0.464	0.660	0.962
Engineering & Design Costs 6% of TFCI	0.464	0.660	0.962
Total Facilities Construction Investment (TFCI)	7.731	11.002	16.039
Initial Charge of Catalyst, Chemical - 3% of FCI	0.177	0.253	0.368
Start-Up Costs 20% of Gross Operating Cost	0.997	1.173	1.266
Paid Up Royaltie 1% of TFCI	0.077	0.110	0.160
Total Plant Investment (TPI)	8.892	12.538	17.833
Working Capital 10% of TPI	0.898	1.254	1.783
Allowance for Funds Used During Construction	0.898	1.254	1.783
Total Capital	10.778	15.045	21.399

Table 26

Annual Operating Costs for a 6 x 10^9 Btu/Day Fixed-Bed Coal Gasification Plant

(Units in Millions of Dollars, 4th Quarter, 1986)

	Case A	Case B	Case C
	Hot Raw Gas	Cold Clean Gas Without Sulfur Removal	Cold Clean Gas Wtih Sulfur Removal
Raw Material	3.247	3.895	3.993
Other Material & Operating Cost			
3% of FCI	0.177	0.253	0.368
Labor			
Process Operating Labor	0.513	0.513	0.513
Maintenance Labor	0.089	0.126	0.184
Overhead Cost	0.783	0.831	0.906
Maintenance Material	0.059	0.084	0.123
Local Taxes & Insurance			
1.5% of TFCI	0.116	0.165	0.241
Gross Annual Operating Cost	4.984	5.867	6.328
By-Product Credit			
Sulfur	-	-	0.245
Tar/Oil	-	0.315	0.339
Net Annual Operating Cost	4.984	5.552	5.744

Notes:

- Raw coal cost = $1.50/106 Btu.
- On-stream factor = 90%.
- Process operating labor = (6 men/shift)(8304 man-hour/year)($10.30/man-hour).
- Overhead cost = (1.3)(Labor).
- By-Product Credit - Sulfur Tm $90/ton, Tar/oil Tm $0.20/gal.

Table 27

Product Cost for a 6 x 10[9] Btu/Day Fixed-Bed Coal Gasification Plant

	Case A	Case B	Case C
	Hot Raw Gas	Cold Clean Gas Without Sulfur Removal	Cold Clean Gas With Sulfur Removal
Total Capital Costs, 10^6 \$	10.778	15.045	21.399
Annual Operating Costs, 10^6 \$	4.984	5.552	5.744
Levelized Cost of Product Gas, \$/10^6 Btu	3.43	4.08	4.71

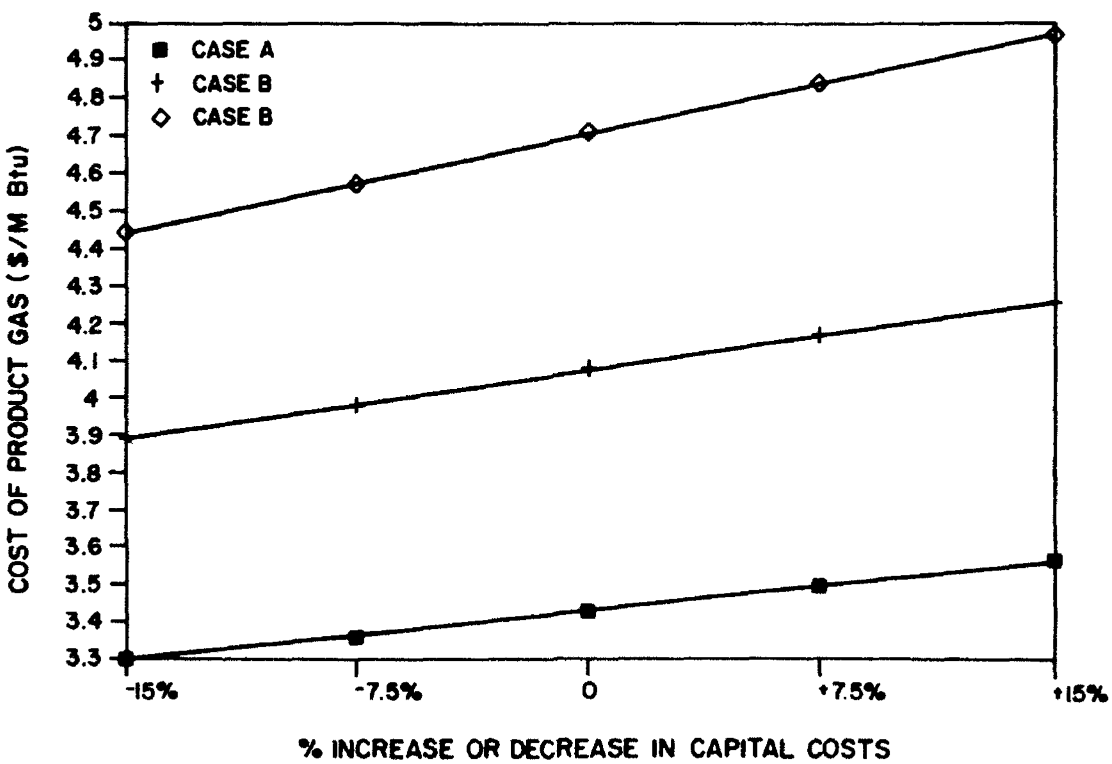

Figure 28. Sensitivity of product gas cost to capital cost.

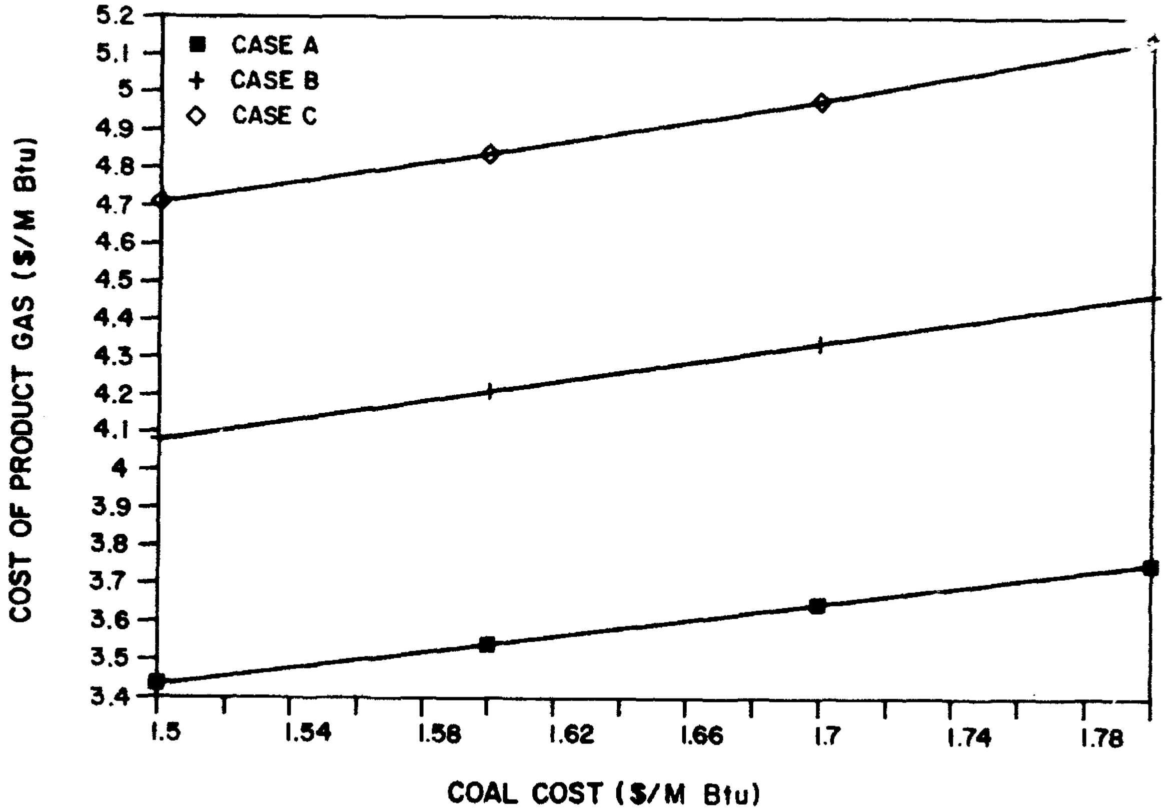

Figure 29. Sensitivity of product gas cost to coal cost.

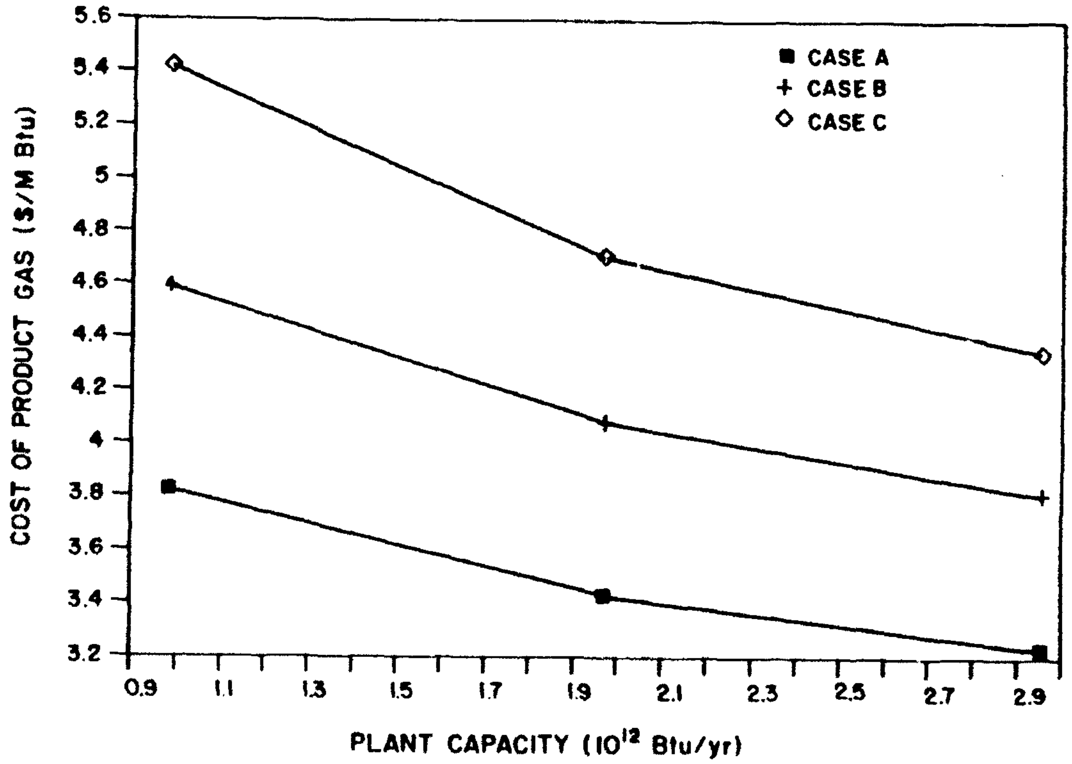

Figure 30. Sensitivity of product gas cost to plant capacity.

Oxidative pretreatment reduces the caking tendency of highly caking coal by partial oxidation of the coal particle surface. However, this process is at the sacrifice of up to one-third of the volatile matter in the raw coal and a decrease of solids bulk density of nearly 50 percent. Winkler, the only commercial fluidized-bed process, performs best using lignite and noncaking subbituminous coals; its use of highly caking coal is yet to be demonstrated.

To avoid ash clinker formation, the fluidized bed is generally operated below ash fusion temperature. This lower bed temperature and the uniform composition of bed solids raise the ash discharge carbon content and lower the thermal efficiency. These restrictions can be resolved by effectively creating a "localized" high-temperature zone in the fluidized bed. The local hot zone is at or near the incipient ash-softening point; ash agglomerates are formed and hence the carbon content in the ash discharge is greatly reduced. The Institute of Gas Technology's U-GAS process is a good example of this type of gasifier.

Winkler Process[11]

Raw coal is crushed to 3/8 x 0 in. and dried to remove the surface moisture. Sized and dried (less than 8 percent moisture) coal is fed to the fluidized-bed in the lower portion of the gasifier by lockhoppers and a variable speed screw feeder (Figure 31). The coal is gasified in the bed by the reactant gases injected from the bottom of the gasifier. Approximately 70 percent of the coal ash is carried over by the high-velocity ascending gas stream; the remaining heavy ash particles are removed from the bottom of the gasifier by water-cooled screw conveyors. Unreacted carbon contained in the entrained particles is further gasified by the additional reactant gases injected in the large space above the bed. The operating pressure is slightly above atmospheric and the gasification temperature ranges from 1500 to 2000 °F, depending on coal reactivity and ash fusion temperature. The ascending hot gas flows through a radiant-heated boiler in the dilute phase of the gasifier where the gas and entrained particles are cooled, thus minimizing ash particle melting. This feature prevents possible refractory damage due to ash sintering. It also permits higher operating temperature for less reactive feedstocks.

The raw gas leaving the gasifier is cooled to about 1300 °F in the radiant-heated boiler where steam is generated. The gas then passes through a waste heat boiler to recover the sensible heat and then through a dry cyclone. Entrained particles are removed in both the waste heat boiler and the cyclone. Product gas is further cooled and cleaned by wet scrubbing and, if required, an electrostatic precipitator can be included. The material balance around a 3-atm Winkler gasifier is given in Table 28.

Ash removed in the dry state is conveyed pneumatically to a remote ash bunker. The ash discharged from the bottom of the gasifier is recovered as slurry in a settler and then mixed with the warm dry ash where the contained water cools and wets it to prevent dusting problems during final disposal.

The Winkler process is fully commercialized for production of low- and medium-Btu gas when operated at or near atmospheric pressure. The best performance is obtained when using reactive coals such as lignite and noncaking subbituminous coals. An 18-ft-diameter unit can gasify up to 700 ton/day of coal using steam/air as the gasifying agents, and up to 1100 ton/day of coal using steam/oxygen as the gasifying agents. Seventy commercial gasifiers have been built at 24 locations. Table 29 lists the commercial units built since 1926.

[11] W.W. Bodle and J. Huebler; *Synthetic Fuels Data Handbook*, 2nd ed. (Cameron Engineers, Inc., Denver, CO 1978).

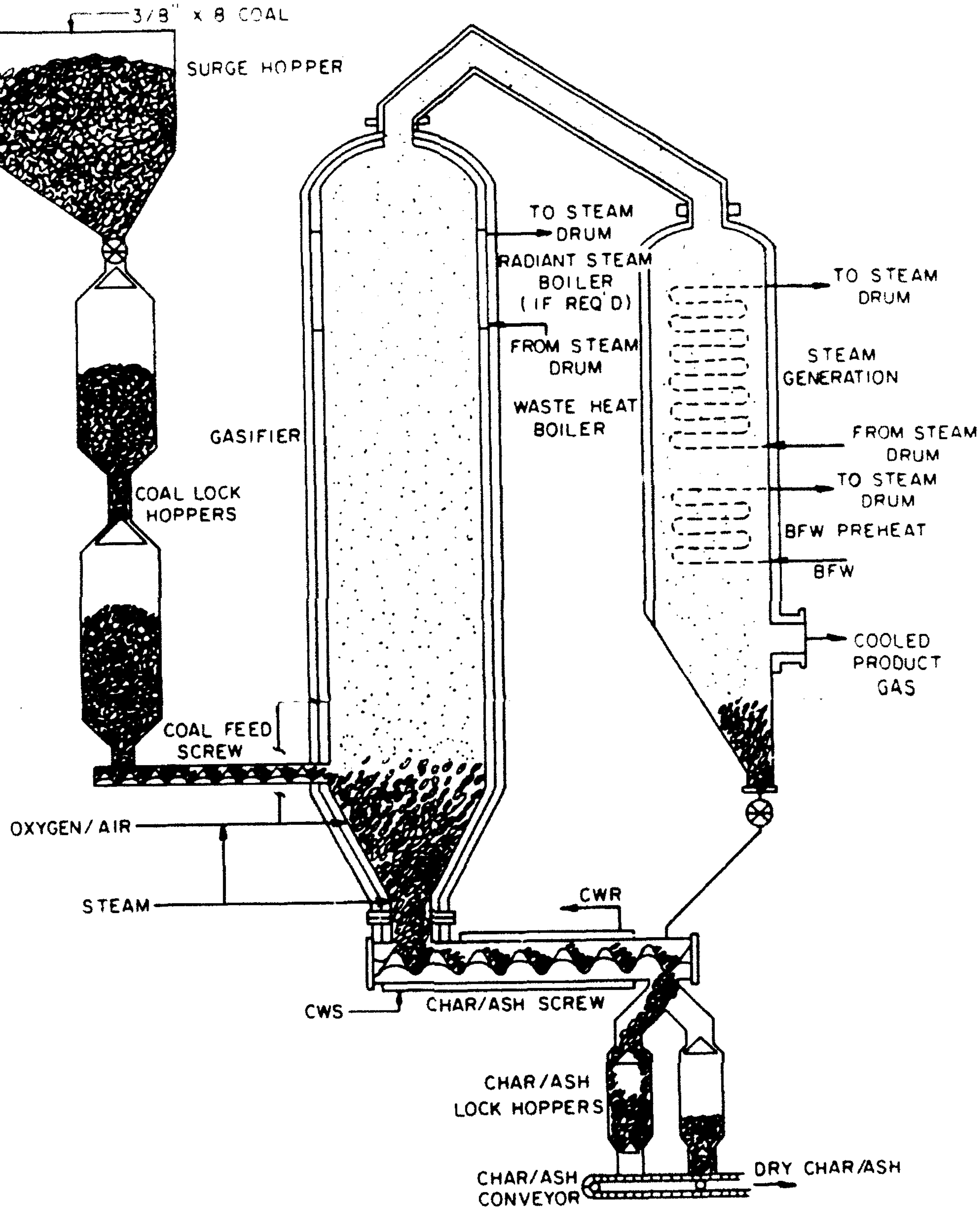

Figure 31. Winkler fluidized-bed-gasifier.

Table 28

Material Balance of a 3-Atm Gasifier

(Product Gas Cooled to 104 °F)

Basis: 1 lb Coal	Oxygen-Blown Gasifier	Air-Blown Gasifier
In: (a) Coal, wt %		
Carbon	48.36	48.36
Hydrogen	3.61	3.61
Oxygen	11.23	11.23
Nitrogen	0.86	0.86
Sulfur	0.57	0.57
Water	16.50	16.50
Ash	18.87	18.87
	100.00	100.00
(b) Reaction Stem, lb	0.50	0.08
(c) Oxygen, lb (98% vol)	0.437	—
(d) Air SCF	—	32.048
Out: (a) Product, Raw Gas, Mol %		
CO_2	219.40	7.12
CO	34.70	22.01
H_2	41.74	13.93
CH_4	3.09	0.82
N_2	0.93	55.99
H_2S	0.12	0.02
COS	0.02	0.02
	100.00	100.00
Water, Vol/Vol of Dry Gas	0.036	0.036
Product Dry Gas Rate, SCF	23.80	45.42
Dust in product Gas, Grains/1000 SCF	1.0	1.0
Product Gas Pressure, psig	16	16
(b) Dry Char, wt %		
Carbon	21.66	21.99
Ash	78.34	78.01
	100.00	100.00
Dry Char, lb	0.23	0.23
(c) Wet Char		
Solids	25.00	25.00
Water	75.00	75.00
	100.00	100.00
Char in Slurry, lb	0.04	0.04
(d) Waste Water, lb	0.38	0.38
Gasifier Carbon Efficiency: $\frac{\text{C in gas from the Winkler plant}}{\text{C in coal to the Winkler plant}}$	89.21	89.08

Table 29

Davy "Winkler" Coal and Coke, Fluid-Bed Gasification Plants

Plant No.	Plant	Product	Capacity Per Gasifier, 1,000 SCF/hr	Number Gasifiers	Operating Dates
1	BASF, Ludwigshaven West Germany	Pilot Plant	75	1	1925-58
2	Leuna-Werke, Merseburg, East Germany	Fuel gas and synthesis gas for MeOH and NH_3	3,730 1,870	4 1	1926-70
3	BRABAG, Bohlen, East Germany	Hydrogen	1,120	3	1938-present
4	BRABAG, Madeburg, East Germany	Hydrogen	1,230	3	1938-45
5	Yahagi, Japan	Ammonia	330	1	1937-60
6	Dai-Nihonyinzo-Hiryo, Japan	Ammonia	520	2	1937-59
7	Nippon Tar, Japan	Ammonia	750	2	1938-69
9	Fushum, Mandschukko,* Japan	Syn gas for F.T. fuel	750	4	1939-?
10	BRABAG, Zeit, East Germany	Hydrogen	840	3	1941-present
11	Treibstoffwerke, Brux (now Most), Czechoslovakia	Hydrogen	1,120 1,200 *	5 2	1943-73 1954-73
12	Salawad, U.S.S.R.**	Medium-Btu gas	860	7	?-present
13	Baschkirien, U.S.S.R**	Medium-Btu gas	860	4	?-present
14	Kombinat, Schwarze Pumpa, East Germany**	Low-Btu gas	2,400	6	?-present
15	Dimitroffgrad, Bulgaria**	Medium-Btu gas	670	4	1951-present
16	Stara Zagora, Bulgaria**	Medium-Btu gas	1,120	5	1962-present
17	Fabrika Azotnih, Jendinjenja, Gorazde, Yugoslavia	Ammonia	260	1	1952-present
18	Calvo Sotelo I, Puertollano, Spain	Ammonia	350	1	1956-70
19	Calvo Sotelo II,	Ammonia	350	1	1959-70
20	UKW, Wesseling I, West Germany	Synthesis gas for MeOH and NH_3	630	1	1958-67
21	UKW, Wesseling II, West Germany	Synthesis gas for MeOH and NH_3	630	1	1962-67
22	Azot Sanayii TAS, Kutahya Turkey	Ammonia	450	2	1959-present
23	Meyveli Lignite Corp., India	Ammonia	745	3	1961-present
24	UK — Wesseling HTW,* West Germany	Demonstration Plant	60	1	1978-present
24	(Including Pilot Plants)			70	(Including pilot plants)
11	---------------IN OPERATION AT PRESENT---------------			39	

* Replica Winkler plants built by others.
** Plants in the Soviet Bloc which were built as replicas of existing plants

AS OF 1/24/79

U-GAS Process[12]

The U-GAS process was developed by the Institute of Gas Technology (IGT) to produce a low- to medium-Btu fuel gas from a variety of feedstocks including highly caking, high-sulfur, and high-ash coals. The U-GAS process accomplishes four important functions in a single-stage fluidized-bed gasifier: it decakes, devolatilizes, and gasifies coal, and agglomerates and separates ash from the reacting char.

Crushed coal (1/4 in. x 0) is dried only to the extent required for handling. As shown in Figure 32, the coal is injected pneumatically into the gasifier through a lockhopper system. Within the fluidized bed, coal reacts with steam and oxygen (air can be substituted for oxygen) at a temperature of 1750 to 2000 °F. The bed temperature depends on the type of coal feed and is controlled to maintain nonslagging conditions for the ash. The operating pressure of the process depends on the ultimate use of the product gas and may vary between 50 and 450 psi. At the specified conditions, coal is rapidly gasified and produces a gas mixture of hydrogen, carbon monoxide, carbon dioxide, water and methane, in addition to hydrogen sulfide and other trace impurities. Because reducing conditions are always maintained in the bed, nearly all of the sulfur present in the coal is converted to hydrogen sulfide, which is simpler and less costly to remove by conventional means than is sulfur dioxide.

As the coal gasification reactions progress, the ash concentration of particles in the fluidized bed increases. As the particulate ash concentration increases, a condition is reached such that, ideally, the particles agglomerate into small spheres, which are denser than the bed composite and can thus be selectively removed from the bed. As shown in Figure 32, fluidizing gas is introduced into the reactor in two areas: (1) through the sloping distributor grid at the bottom of the bed; and (2) through the ash-discharge device, consisting of a Venturi/classifier system, located at the center of the distributor plate.

The oxygen-to-steam ratio in the two gas-entry streams is controlled so that a greater ratio is maintained in the ash-discharge device. By this mechanism, a higher temperature is maintained in the bottom of the bed in the central zone, where the high ash concentration particles selectively stick to each other at the incipient softening temperature of the particles. The agglomerates grow until their mass can no longer be supported by the gas rising through the Venturi/classifier. They are removed by gravity and discharged from the bed through the classifier section into water-filled ash hoppers where they are then withdrawn as a slurry. By this technique, the gasifier achieves a low level of carbon loss in the discharge ash, which produces an overall carbon conversion of 95 percent or greater. Figure 32 also shows that the fines elutriated from the fluidized bed are separated from the product gas in two stages of external cyclones. The fines from the first stage are returned to the bed, and those from the second stage are returned to the ash-discharge zone where they are completely gasified. The ash contained in the reinjected fines also forms agglomerates and is discharged from the bed. The product gas is virtually free of tars and oils due to the relatively high temperature of the fluidized-bed operation, which simplifies the ensuing heat-recovery and gas cleanup steps.

IGT, with U.S. Government and industrial support, has been developing the U-GAS process since 1974 through a pilot plant program conducted with U.S. and foreign coals and coal chars. The U-GAS technology is now available for licensing from GDC, Inc., a wholly-owned subsidiary of IGT. Figure 33 is a process flow diagram of the pilot plant. More than 10,000 hr of operating time have been logged in the pilot plant, during which period over 120 tests have been conducted with more than 3500 tons of various feedstocks (Table 30). Several test runs have lasted longer than 2 weeks, providing long, steady-state operation with good material and energy balance closures. Typical balances with various feedstocks are shown in Figures 34 and 35. The range of feedstock properties is summarized in Table 31.

[12] A. Goyal and A. Rehmat, "The U-GAS Process--From Research to Commercialization," presented at the Annual Meeting of the American Institute of Chemical Engineers, San Francisco, CA (1984).

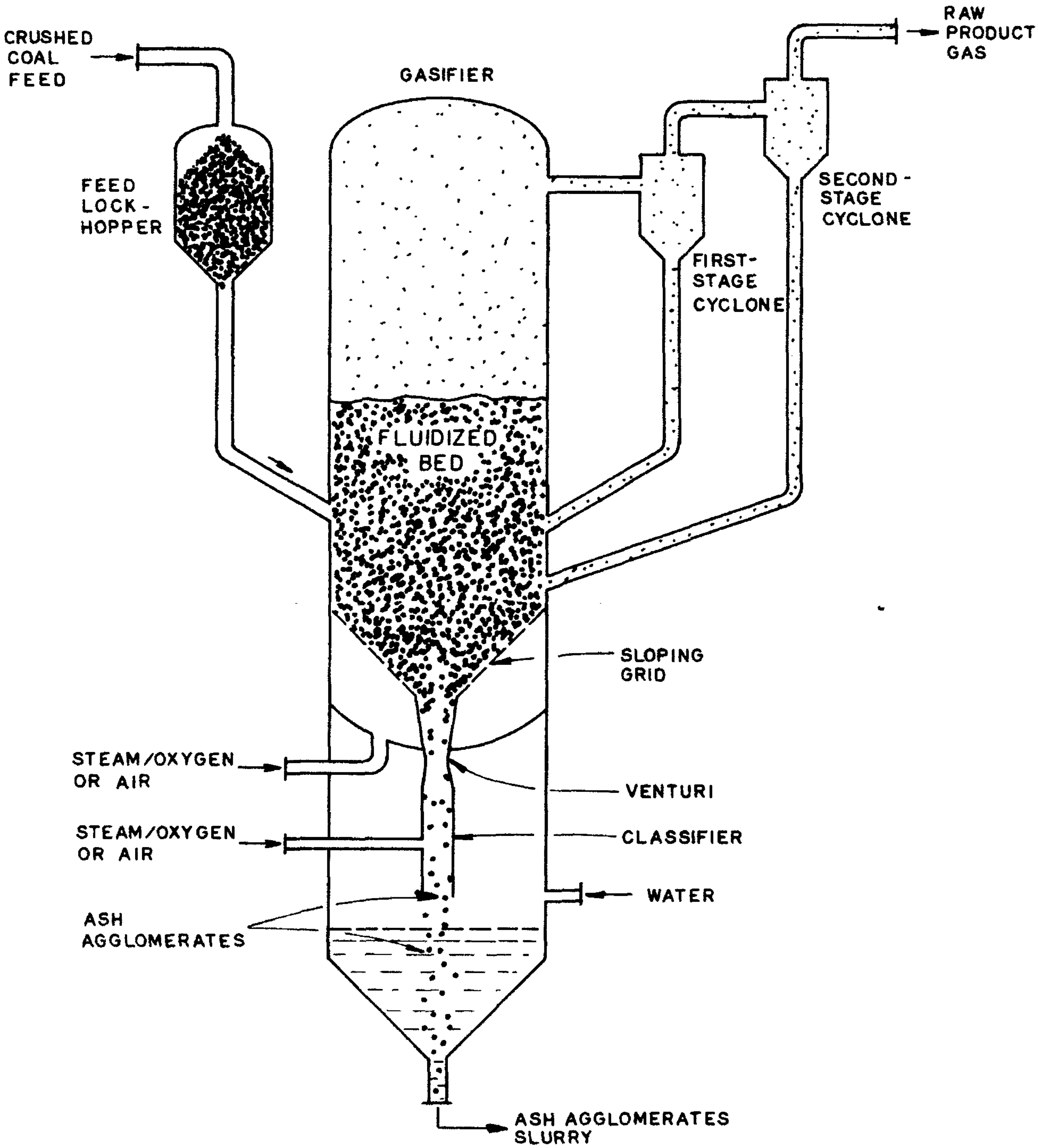

Figure 32. The U-GAS gasifier.

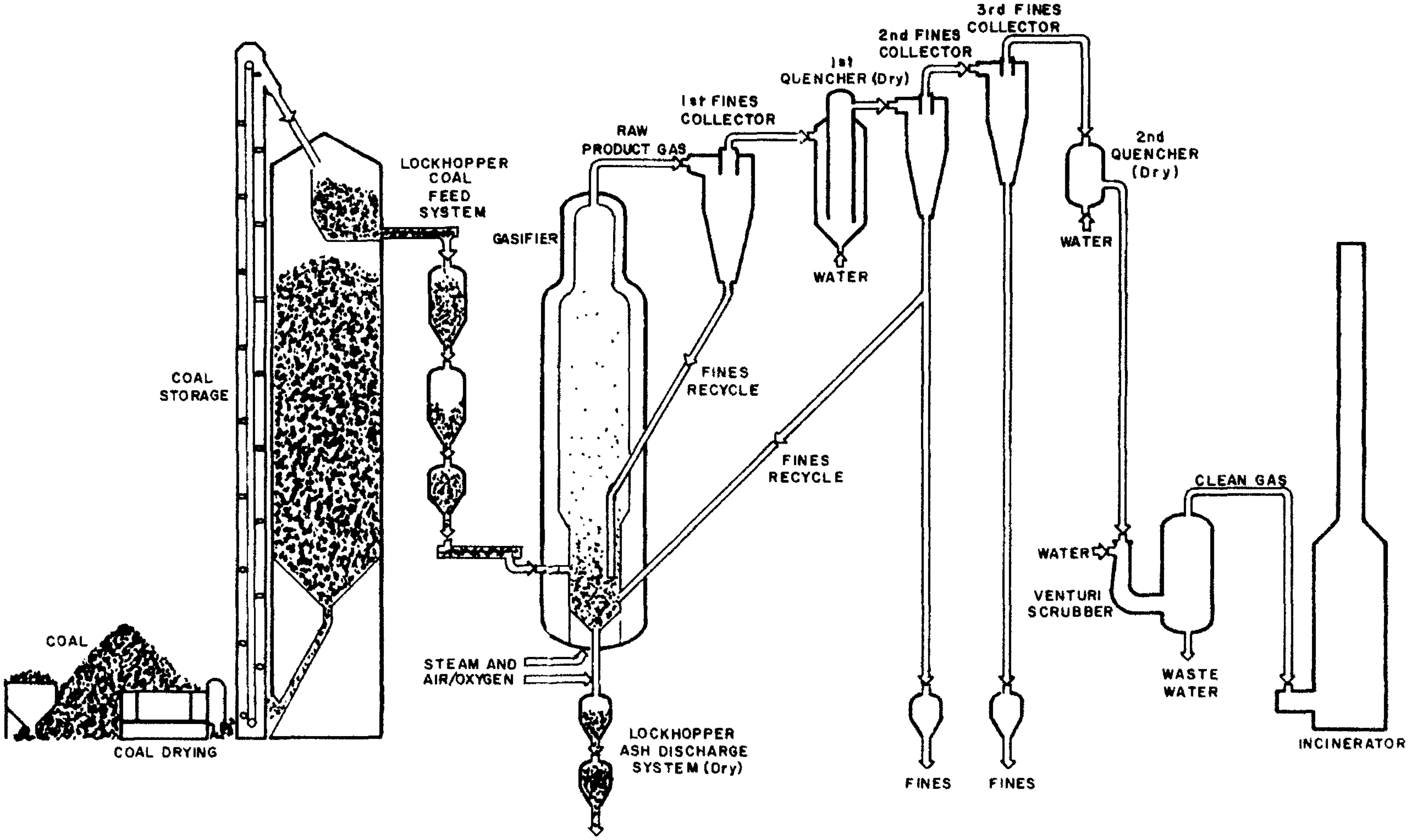

Figure 33. Process flow of the U-GAS pilot plant.

Table 30

U-GAS Gasifier Feedstocks

- Western Kentucky No. 9 Bituminous
  (both washed and unwashed)
- Western Kentucky No. 11 Bituminous
- Illinois No. 6 Bituminous
- Pittsburgh No. 8 Bituminous
- Australian Bituminous
- Polish Bituminous
- French Bituminous (unwashed)
- Utah Bituminous (unwashed)
- Montana Subbituminous
- Wyoming Subbituminous
- Metallurgical Coke
- Western Kentucky Coal Char
- Illinois No. 6 Coal Char

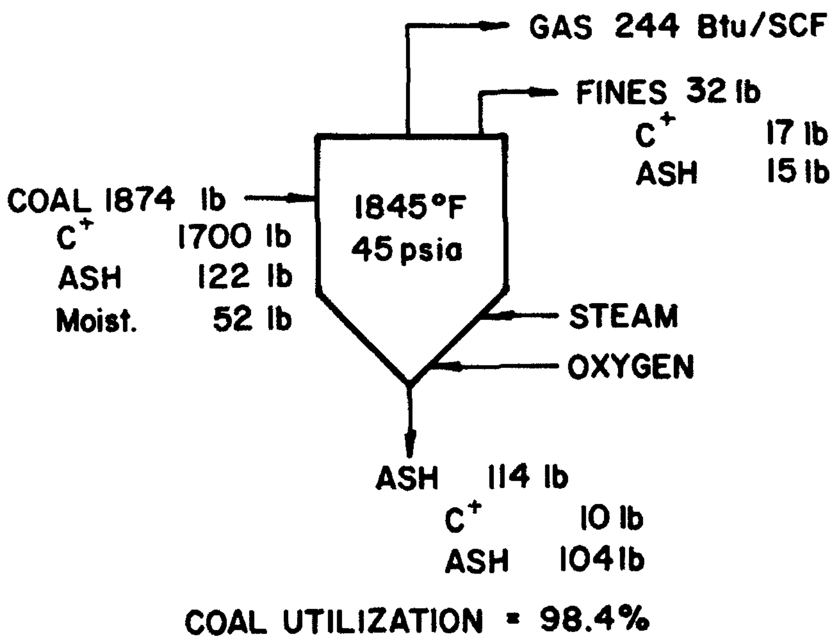

Figure 34. Pilot plant data—Western Kentucky No. 9 coal feed.

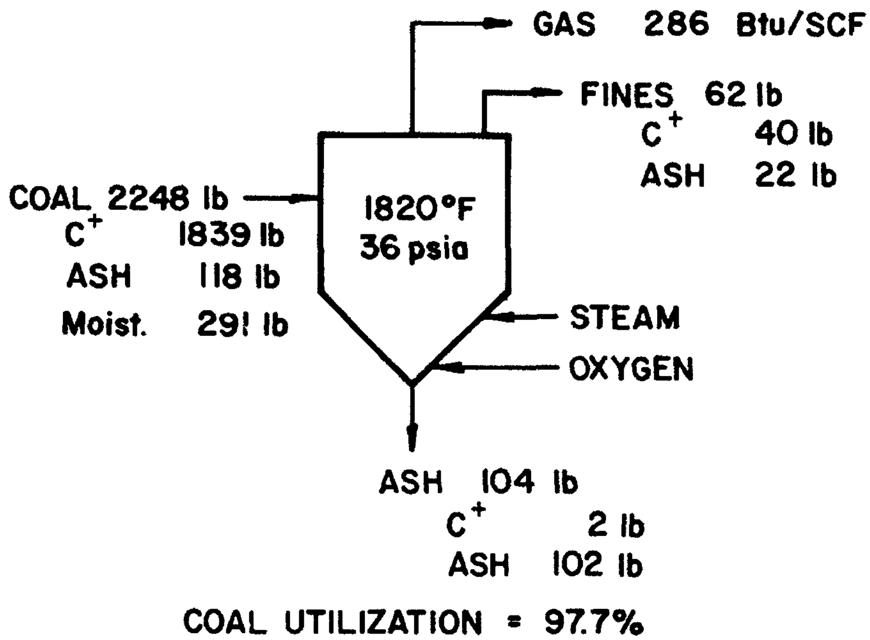

Figure 35. Pilot plant data—Wyoming subbituminous.

Table 31

Range of U-GAS Gasifier Feedstock Properties

Moisture,* %	1 to 32
Volatile matter,** %	3 to 43
Ash,** %	6 to 35
Sulfur,** %	0.5 to 4.6
Free swelling index	0 to 8
Ash softening temperature, °F (°C)	1,980 to 240 (1,080 to 1,370)
Gross heating value,* Btu/lb (kJ/kg)	7,580 to 12,650 (17,631 to 29,424)

* As received.
**Dry basis.

Commercial Entrained-Bed Gasifier[13]

Overview

In an entrained-bed gasifier, pulverized coal particles (80 percent through 200 mesh) are conveyed pneumatically or entrained by the reactant gases at velocities in excess of the flame propagation rate into the reaction zone. The gasification reactions occur more at relatively high temperature (2500 to 3000 °F) and with a very short reaction time, usually a few seconds. Coal particles are rapidly devolatilized and lose all inherent characteristics of the original coal. Therefore, all types of coal can be directly gasified in an entrained-bed unit. The high operating temperature eliminates tar and oil formation, which significantly reduces the raw gas cleanup requirements. The mineral content of the coal is in molten form at high temperatures. Part of it is removed from the bottom of the gasifier as a liquid slag. The rest of the ash is carried overhead by the raw product gas and is removed in the downstream gas scrubber.

The entrained-bed gasifier offers many advantages such as the ability to handle all types of coal, elimination of tar and oil formation, and fewer raw gas cleanup requirements. However, problems are introduced by the high operating temperatures, such as shortened refractory service life and poorer slag viscosity control. In addition, the rapid reaction rate and lack of carbon inventory in the gasifier require good process control to prevent free-oxygen breakthrough if the coal feed is interrupted. The lack of carbon inventory in the gasifier can also decrease the system turndown ratio.

Koppers-Totzek Process[14]

The Koppers-Totzek process is the most widely used commercial example of the entrained-bed gasifier. Figure 36 is a process schematic for producing clean, desulfurized utility gas or synthesis gas. Depending on rank, the coal is dried to between 2 and 8 percent moisture and pulverized to about 70 percent passing through 200 mesh. The coal is conveyed with nitrogen from storage to the gasifier service bins. Controls regulate the intermittent feeding of coal from the service bins to the feed bins, which are connected to variable-speed coal screw feeders. The pulverized coal is discharged continuously into a mixing nozzle where it is entrained in a mixture of oxygen and low-pressure steam. Moderate temperature and higher burner velocity prevent the reaction of coal and oxygen prior to entering the gasification zone.

Pulverized coal is gasified in suspension with oxygen and steam in the gasifier. The gasifier is a refractory-lined steel shell equipped with a steam jacket for producing low-pressure process steam. A two-headed gasifier, capable of gasifying over 400 ton/day of coal, is shown in Figure 37. Coal, oxygen, and steam are brought together in opposing gasifier burner heads spaced 180 degrees apart. Four-headed gasifiers, capable of gasifying 850 ton/day of coal, employ burner heads 90 degrees apart. Reaction temperature at the burner discharge is 3300 to 3500 °F, and operating pressure within the gasifier is slightly above atmospheric. The coal is gasified almost completely and instantaneously. Gaseous and vaporous hydrocarbons emanating from the coal at medium temperatures are passed through a zone of very high temperature in which they decompose so rapidly that coagulation of coal particles during the plastic stage does not occur. Thus, all ranks of coal can be gasified directly without pretreatment.

The coal ash is converted into molten slag. About 50 percent of this slag drops into a quench tank below the gasifier and is carried to the plant disposal system as granular solids. The remaining ash is carried out of the gasifier by the exit gas as fine fly ash.

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[13] W.W. Bodle and J. Huebler; J.F. Farnsworth, H.F. Leonard, D.M. Mitsak, and R. Wintrell, *The Production of Gas From Coal Through a Commercially Proven Process* (Koppers Co., Inc., Pittsburgh, PA, 1973).

[14] J.F. Farnsworth, et al.

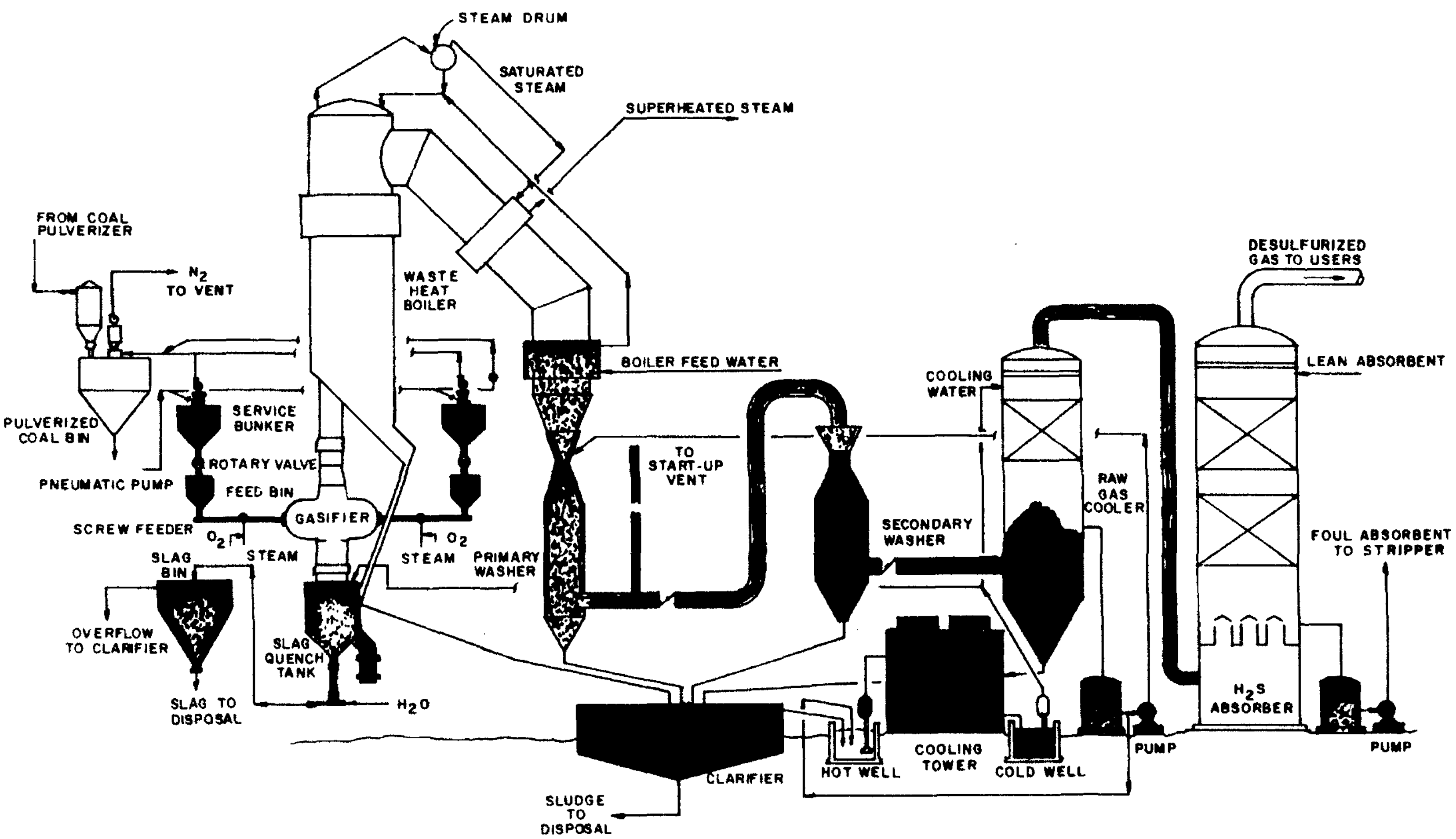

Figure 36. Koppers-Totzek coal gasification process.

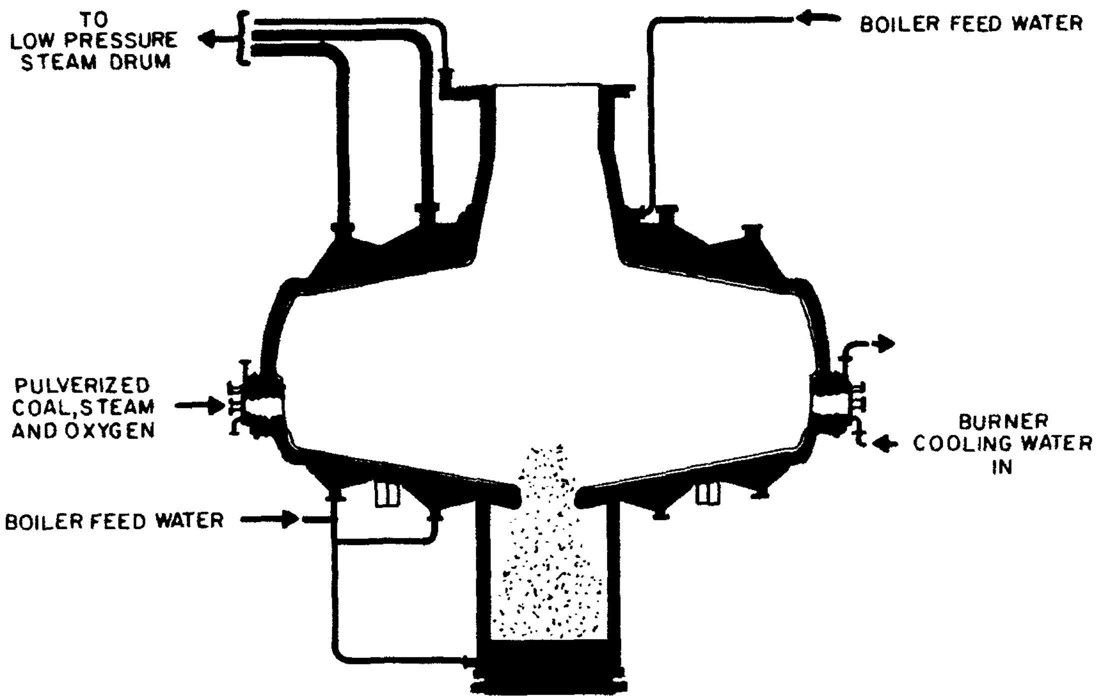

Figure 37. Two-headed Koppers-Totzek Gasifier.

The raw gas leaves the gasifier at about 2750 °F. At this high temperature, no tars, condensable hydrocarbons, or phenols are formed. The gasifier outlet is equipped with water sprays to drop the gas temperature below the ash fusion temperature, if necessary. This step prevents slag particles from adhering to the tubes of the waste heat boiler mounted atop the gasifier. Flux can be added to the coal feed to adjust to ash fusion characteristics. Low-pressure steam produced in the gasifier jacket is returned to the gasifier as process steam. High-pressure steam produced in the waste heat boilers can be used onsite in turbine drives for compressors and pumps, or may be exported.

Gas leaving the gasifier can be water quenched directly to solidify entrained slag droplets, and then passed through a waste heat boiler where high-pressure steam of up to 1500 psig is produced. After leaving the waste heat boiler, the gas is cleaned and cooled in a high energy scrubbing system, which reduces the entrained solids to 0.002-0.005 grains/SCF and lowers the temperature from 350 °F to about 95 °F. Sulfur compounds are removed from the cold clean gas by standard desulfurization if necessary. Particulate-laden water from the gas cleanup system is piped to a clarifier. Sludge from the clarifier is pumped to a filter or to the plant disposal area. The clarified water is recirculated through Venturi scrubbers. Table 32 lists typical gasification data for Western subbituminous, Illinois high-volatile B bituminous, and Eastern high-volatile A bituminous coals.

Carbon conversion is a function of the coal reactivity, which increases with decreasing coal rank. Carbon conversion for lignites and young subbituminous coals approaches 100 percent, decreasing to 95 to 97 percent for high-volatile A coals. The composition and heating values of the product gases are similar in all cases, regardless of the feedstock used; the main components are carbon monoxide and hydrogen. A heat balance based on Eastern coal is given in Table 33, and Table 34 is a partial list of commercial Koppers-Totzek installations.

Table 32

K-T Gasifier Data for U.S. Coals

Property	Western Coal	Illinois Coal	Eastern Coal
Gasifier Feed			
Dried Coal to Gasifier Analysis, Vol %			
C	56.76	61.94	69.88
H_2	4.24	4.36	4.90
N_2	1.01	0.97	1.37
S	0.67	4.88	1.08
O_2	13.18	6.73	7.05
Ash	22.14	19.12	13.72
Moisture	2.00	2.00	2.00
Gross Heating Value Btu/lb	9,888.00	11,388.00	12,696.00
Oxygen-NT/NT Dried Coal	0.649	0.704	0.817
Purity-%	98.0	98.0	98.0
Process Steam, lb/NT Dried Coal	272.9	541.3	587.4
Gasifier Products			
Jacket Steam, lb/NT Dried Coal	347.8	404.9	464.9
High Press. Steam, lb/NT Dried Coal	2,147.1	2,292.2	3,023.6
Raw Gas Analysis (Dry Basis), Vol %			
CO	58.68	55.38	55.90
CO_2	7.04	7.04	7.18
H_2	32.86	34.62	35.39
N_2	1.12	1.01	1.14
H_2S	0.28	1.83	0.35
COS	0.02	0.12	0.04
TOTAL	100.00	100.00	100.00
Gross Heating Value, Btu/SCF	295.1	290.2	294.4
Gas Make, SCF/NT Dried Coal	51,783.	59,489.	66,376.
Slag Make, NT/NT Dried Coal	0.222	0.190	0.138
Process Efficiency	88.2	85.0	90.3
Coal-to-Gas Efficiency	77.3	75.8	77.0

Table 33

K-T Gasifier Heat Balance

Heat Input—Above 60 °F	Btu/NT Coal As Charged
Calorific Value of Coal	25,392,000
Sensible Heat in Coal at 160 °F	57,000
Sensible Heat in Oxygen at 220 °F	57,240
Total Heat in Steam at 250 °F	667,290
Total	26,173,530
Heat Output—Above 60 °F	
Heat in Molten Slag and Ash	218,700
Sensible Heat in Unburned Carbon	74,680
Calorific Value of Unburned Carbon	984,930
Calorific Value of Gas	19,708,380
Sensible Heat, Dry Gas	3,763,920
Total Heat, Water Vapor in Gas	912,910
Total Heat, Gasifier Jacket Steam	453,910
Subtotal	26,117,430
Gasifier Heat Loss	56,100
Total	26,173,530

* Based on Eastern coal with 2% moisture and 2732 °F gas temperature.

Table 34

Tabulation of Existing Koppers-Totzek Plants

Location/ Company	Feedstock	Number Of Gasifiers	Capacity m^3 $CO+H_2$ /day	Synthesis	Ordered (year)
Charbonnages de France, Paris Mazingarbe Plant, France	Bituminous Coal Dust, Coke-Oven Gas Residual Gas	1	75,000-150,000	Methanol and Ammonia Synthesis	1949
Typpi Oy, Oulu, Finland	Bituminous Dust, Oil, Peat	3	140,000	Ammonia Synthesis	1950
Nihon Suiso Kogyo Kaisha, Ltd., Tokyo, Japan	Bituminous Coal Dust	3	210,000	Ammonia Synthesis	1954
Nitrogen Plant in Puentes de Garcia Rodriguez (Coruna), Spain	Lignite Dust	3	242,000	Ammonia Synthesis	1954
Typpi Oy, Ouly, Finland	Bituminous Coal Dust, Oil, Peat	2	140,000	Ammonia Synthesis	1955
S.A. Union Chimique Belge, Brussels, Zand-voorde Plant, Belgium	Bunker Fuel Oil, Plant can be extend-ed to include coal dust gasification system	2	176,000	Ammonia Synthesis	1955
Amoniaco Portu-gues S.A.R.L., Estarreja Plant	Heavy Naphtha; Plant can be extend-ed to include lignite dust and anthracite dust gasification system	2	169,000	Ammonia Synthesis	1956
Ptolemain Nitrogen Plant, Greece	Lignite Dust Bunker Fuel Oil	4	629,000	Ammonia Synthesis	1959
Nitrogen Plant Puentes de Garcia Rodriguez, Spain (reconstruction)	Lignite Dust Naphtha	1	175,000	Ammonia Synthesis	1961
Attaka Nitrogen Plant, Suez, United Arab Republic	Refinery Residual Gases, L.P.G. and Naphtha	3	778,000	Ammonia Synthesis	1963
Chemical Fertili-zer Company Ltd. of Thailand, Ferti-lizer Plant in Mae Moh, Lampang, Thailand	Lignite Dust	1	217,000	Ammonia Synthesis	1963
Azot Sanayii T.A.S. Ankara, Kurahya Plant, Turkey	Lignite Dust	4	775,000	Ammonia Synthesis	1966
VEB Hydrierwerk Zeitz, German Democratic Republic	Distillation Residues and Fuel Oil	2	360,000	Raw Gas (Hydrogen Production)	1966

Table 34 (Cont'd)

Tabulation of Existing Koppers-Totzek Plants

Location/ Company	Feedstock	Number Of Gasifiers	Capacity m^3 CO+H_2 /day	Synthesis	Ordered (year)
Kobe Steel Ltd., Kobe, Japan, for Industrial Development Corps. of Zambia, Kafue, Lusaka, Zambia	Bituminous Coal Dust	1	214,320	Ammonia Synthesis	1967
Nitrogenous Fertilizers Industry S.A., Athens, Ptolemais Nitrogen Plant, Greece	Lignite Dust	1	165,000 Synthesis	Ammonia	1969
The Fertilizer Corps. of India, New Dehli, Korba Plant, India	Bituminous Coal Dust	3	2,000,000	Ammonia Synthesis	1969
The Fertilizer Corp. of India, New Delhi, Talcher Plant, India	Bituminous	3	2,000,000	Ammonia	1970
Nitrogenous Fertilizers Industry S.A., Athens, Ptolemais Nitrogen Plant, Greece	Lignite Dust	1	242,000	Ammonia	1970
AE & CI Ltd., Johannesburg, Modderfontain Plant, South Africa	Bituminous Coal Dust	6	2,150,000	Ammonia Synthesis	1972
Indeco Chemicals Ltd., Lusaka, Kafue Zambia	Bituminous Coal Dust	1	220,800	Ammonia Synthesis	1974
Indeco Chemicals Ltd., Lusaka Kafue Zambia	Bituminous Coal Dust	2	441,600	Ammonia Synthesis	1974
Petrobras, San Jeronimo, Brazil	Bituminous Coal Dust	2	1,300,000	Ammonia Synthesis	1979

4 RECENT LOW-BTU GAS COAL GASIFICATION PLANT DEMONSTRATIONS

In 1976, the U. S. Energy Research and Development Administration (ERDA), the predecessor of DOE, established the Gasifiers in Industry program to allow construction of several small gasifiers in a relatively short period of time. The objectives of the program were to:

- Demonstrate low-Btu gasification by integrating these units into several applications in different operating environments

- Accumulate data on the gasifier operation; these data were to include design conditions, actual operation, and environmental and economic assessments

- Decrease the use of natural gas and oil for a limited number of users until more advanced technology is available.

Six projects were chosen initially for Government support. These projects were proposed by the University of Minnesota, Acurex, Pike County, KY, General Refractories, Land O'Lakes, and Irvin Industries. The last three were terminated prior to construction because of cost escalation or local opposition due to environmental concerns.

The Pike County project also was terminated in 1981 prior to completion of the construction phase. A 6.5-ft-diameter Wellman-Galusha gasifier had been installed in Pike County, KY. The raw gas cleanup system had to be completely redesigned because of the more stringent emission standards imposed by the Clean Air Act as amended in 1977, coupled with the fact that the originally contemplated low sulfur (0.6 percent) coal was not available in the Pike County area and it had to be replaced by a higher sulfur (1 percent) coal. The addition of the sulfur removal unit and process redesign required to meet the new emission standards significantly increased the project costs and delayed the startup schedule. The program was terminated due to this cost escalation.

The Acurex project involved instrumentation and data acquisition and analysis on a Wellman-Galusha gasifier installed at Glen-Gery's plant in York, PA. Low-sulfur anthracite was gasified by steam and air to produce low-Btu gas. The hot raw gas was used directly to fire brick kilns. The University of Minnesota project consisted of the installation and operation of a two-stage Foster Wheeler-Stoic gasifier at the Duluth campus. This gasifier produced low-Btu gas and byproduct tar and oil from Western sub-bituminous coals for combustion in boilers that were previously burning natural gas and fuel oils. Both projects were completed and are described in detail below.

University of Minnesota Project[15]

The University of Minnesota-Duluth (UMD) installed and operated a 10-ft-diameter, 3 ton/hr, two-stage Foster Wheeler-Stoic gasifier with funding partially provided by a Cooperative Agreement from the DOE Gasifiers in Industry program. The gasifier produced low-Btu gas and byproduct tars and oils from Western subbituminous coals for combustion in central heating plant boilers that were previously burning

[15] R.P. Lewis and W.E. Soderberg; M.R. Fuchs, M.A. McDevitt, D.S. Lewis, and C.E. Hudak, *Environmental Assessment Source Test and Evaluation Report--Stoic Low-Btu Gasifier*, Report No. PB86-167-12 (U.S. Environmental Protection Agency, February 1986); G.V. McGurl, "Gasifiers in Industry, Experiences on the First Few Projects," paper presented at the Fifth Annual Conference on Coal Gasification, Liquefaction, and Conversion to Electricity, Pittsburgh, PA (August 1978).

natural gas and petroleum fuel oils. The primary objectives of the project were to evaluate the technical and economic aspects of the gasifier plant in an actual operating environment, and to test the concept of converting natural gas and oil-fired boilers to coal-derived fuels without major modifications. The program started in 1976 when the future availability of natural gas and fuel oils was in doubt; it was ended in 1982.

Project Summary and Conclusions

The Foster Wheeler-Stoic gasifier was designed to gasify nonswelling, noncaking bituminous or subbituminous coals using air and steam at an operating pressure of 1 psig. The major gas cleanup equipment included an electrostatic precipitator for tar removal and a cyclone for dust removal from the raw product gas. The entire gasifier plant was located indoors. The product gas was delivered to the heating plant boilers without cooling or storage.

The gasifier was operated intermittently for a total of 10,500 hr during 11 runs from October 1978 to July 1982. The longest period of uninterrupted, pressurized operation was 103 days and the longest period of hot operation was 201 days. However, major modifications and repairs to the gasifier and the other equipment were required to keep the plant operational. Gasifier plant equipment problems frequently interrupted or terminated operations.

The gasifier plant performance is summarized as follows:

- The gasifier ran successfully with Western United States subbituminous coals. Coals with moisture content greater than 20 percent were difficult to gasify due to size degradation in the gasifier. The highly friable coals were found to be not usable in the UMD gasifier. Obtaining sized coal with the desired properties was a continual problem.

- Coals with 5 percent or less ash resulted in operational problems since insufficient ash was produced to protect the gasifier grate.

- The gasifier thermal efficiency was found to average 87 percent with a Wyoming subbituminous coal and 95 percent with a Montana subbituminous coal during gasifier performance tests.

- Gasifier gas was burned in the boiler without problems or the need for boiler flue gas emission control. The boiler thermal efficiency was found to vary from 65 to 77 percent with excess air from 26 to 62 percent. The boiler thermal efficiency on low-Btu gasifier gas was not significantly different from that with natural gas.

- Gasifier tars were burned successfully in the heating plant boilers. However, the solids content of the tars resulted in rapid pump and burner nozzle wear.

- Gasifier labor requirements were three times greater than originally expected.

The estimated product cost (excluding plant investment) if the gasifier supplied 90 percent of the annual fuel requirements for the UMD heating plant in 1982 was $7.09/MBtu with Wyoming coal. The comparable costs of natural gas and heavy fuel oil were $4.27/MBtu and $4.60/MBtu, respectively. The major fixed cost for gasifier operation was labor. Three men per shift were required to run the plant.

The conclusions and observations reached from the UMD project are summarized as follows:

1. Many previously untried design modifications were made to the gasifier. Therefore, extensive plant adjustments were required before the plant would run.

2. The operation of a low-Btu gasifier needed skilled labor. In actual operation, the UMD gasifier required three times the labor that was planned at the beginning of the project.

3. The gasifier preferred a nonswelling, noncaking, nonfriable, low-sulfur, and high ash-fusion temperature coal. This type of coal is difficult to obtain in the United States.

4. Western United States subbituminous coals would function, with some difficulties, in the UMD gasifier. The cost of these coals in Duluth, MN, due to transportation costs, and the highly friable nature of these coals made them economically unsuitable for UMD operation.

5. The overall thermal efficiency of the UMD coal gasifier-boiler combination was approximately 10 percent less than a coal-fired boiler.

6. The byproduct tar produced by the UMD gasifier could not be handled and burned like a heavy fuel oil due to variable viscosity and the solids content.

7. The UMD gasifier, with the proper coal feed, repairs, and modifications, could have met the original technical expectations to supply coal gas as the only fuel source for heating plant operations.

Process Description

Figure 38 shows the UMD coal gasifier in cross section. The gasifier was installed by Foster Wheeler Energy Corporation (FWEC) of Livingston, NJ. The gasifier design is based on technology licensed to FWEC by Stoic Combustion Pty., Ltd. of Johannesburg, South Africa. Sized coal is fed to the UMD gasifier through a lockhopper located at the top of the gasifier. The drying/coking zone of the gasifier is always filled with coal. The descending coal is completely dried and coked by the sensible heat of hot gases flowing upward from the gasification zone. Part of the gas produced in the gasification zone, the bottom gas, flows through passages in the refractory wall and exits the gasifier without contacting the descending coal in the coking and drying zone. The remaining gas, the top gas, flows through the coking and drying zone. Raw coal is thus dried and devolatilized by the top gas. The flow rate of the top gas is controlled by throttling the bottom gas flow control valve to prevent thermal cracking of the tars produced from devolatilization reactions. The maximum flow rate of top gas is about 75 to 85 percent of the total gas generated in the gasification zone when gasifying subbituminous coal with a moisture content greater than 20 percent. The top gas, exiting the gasifier at a temperature below the dewpoints of tar vapors, flows to an electrostatic precipitator for tar-mist and particulates removal. Particulates are removed from the bottom gas by a refractory-lined hot cyclone. The two gas streams are combined and burned in the boilers. Figure 39 is a schematic of the UMD facility, excluding the coal and ash handling systems.

Air and steam are introduced at the bottom of the gasifier and distributed across the bed through the conical rotating grate. The gasification and combustion zone is water-jacketed and provides all of the steam required for gasification. The residue ash flows by gravity into a rotating water-filled ash pan. Stationary plows in the bottom of the ash pan plow the ash into two buckets that lift the ash up through the water seal and dump it into the ash-handling system. The ash discharge rate is adjusted to achieve an ash-balance operation according to the ash level on the grate measured by poking. The water seal height limits the gasifier operating pressure to about 60 in. water gauge.

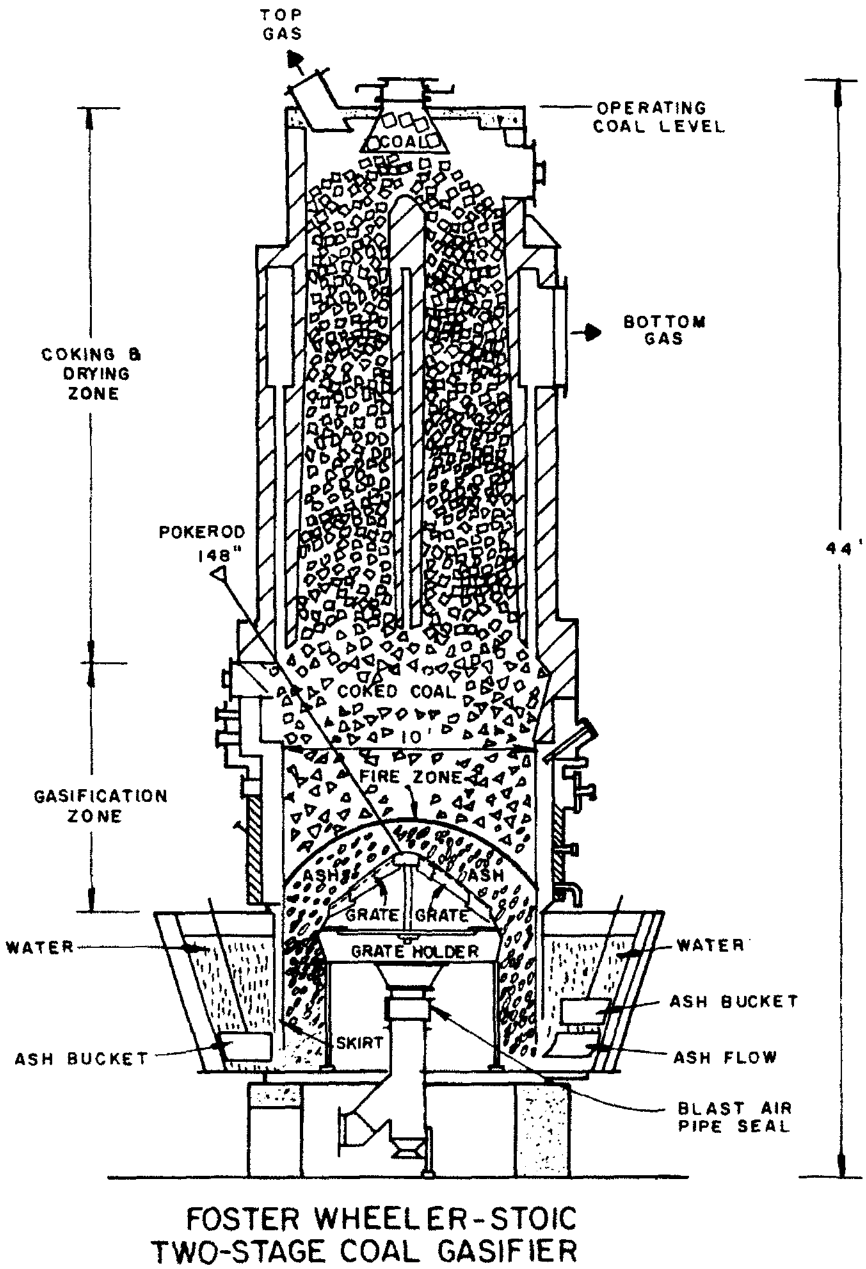

Figure 38. University of Minnesota-Duluth gasifier.

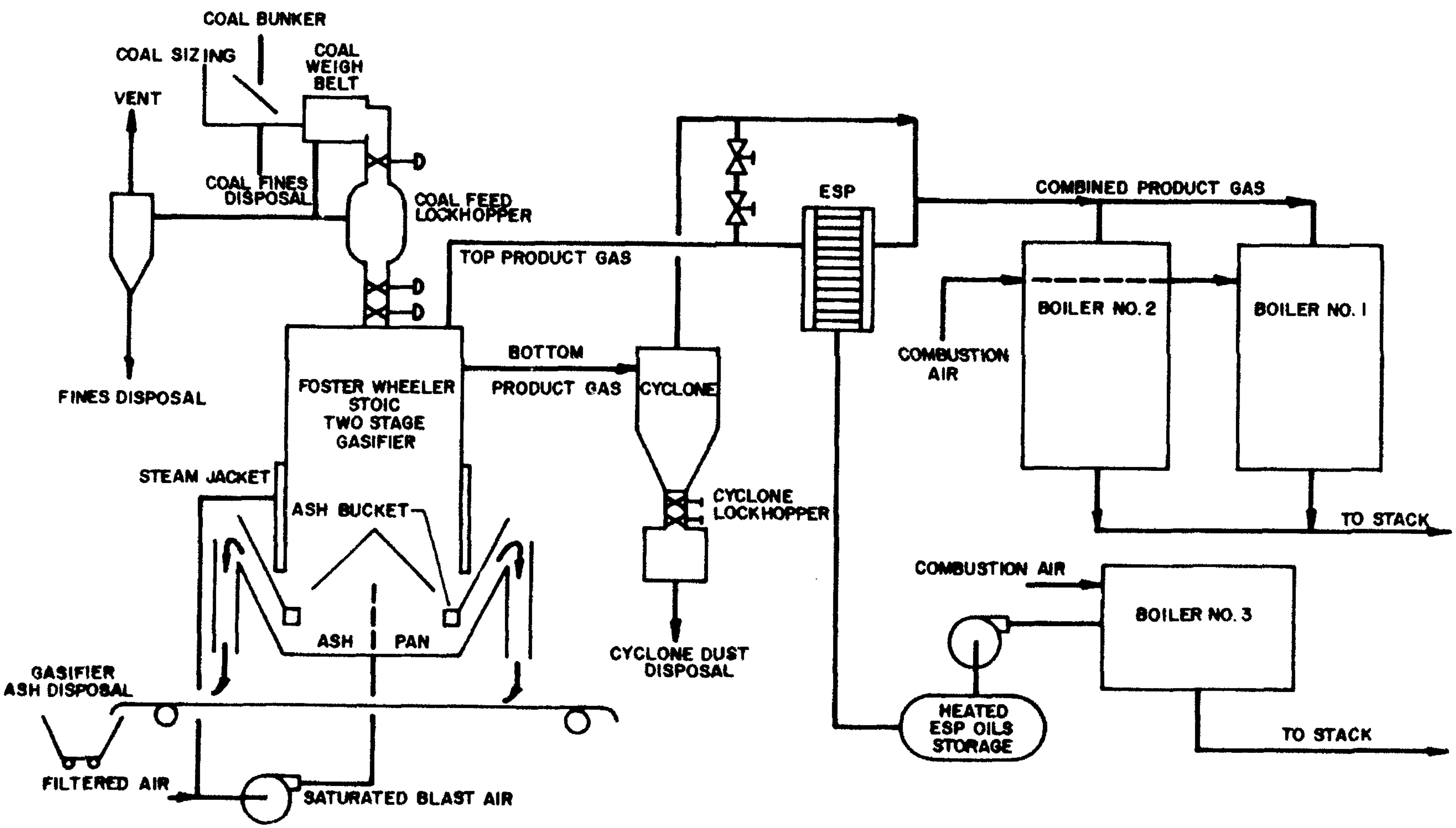

Figure 39. Operation of the Foster Wheeler-Stoic two-stage gasifier at the University of Minnesota-Duluth campus.

Plant Operation and Test Results

The UMD gasifier plant design was based on the Stoic's two-stage gasifier system. However, there were considerable design differences between the 10-ft UMD gasifier and the only other operating 10-ft Stoic gasifier. Some of the major design differences are as follows:

1. The UMD gasifier was designed with an ash pan twice as deep as the Stoic gasifier's.

2. The ash was lifted from the UMD gasifier ash pan by a hydraulic bucket system. The Stoic gasifier used stationary ash plows to lift the ash.

3. The ash was handled at UMD by two closed conveyors, an ash auger, and an ash elevator, and the ash was then stored in a bin. The Stoic gasifier used open conveyors to dump the ash on the ground or into open portable bins.

4. The UMD gasifier plant was fully enclosed and the Stoic plant was partially enclosed at the lockhopper level.

5. The UMD gasifier lockhopper was designed using three valves in series on the feed pipe. The top and bottom valves were butterfly valves. The lockhopper system was operated electrically and pneumatically. The Stoic gasifier used a mechanically controlled rotary drum feed valve.

6. UMD gasifier was totally dependent on the lockhopper for coal feed. The Stoic gasifier coal feed system was equipped with a manual lockhopper bypass chute.

7. The UMD gasifier recycled lockhopper vent gases back to the blast air. The Stoic gasifier lockhopper vent gases were vented directly to the atmosphere.

8. At UMD, coal fines, which amounted to 20 to 40 percent of the coal received, were stored for shipping to a coal-burning steam generation plant. Fines from the Stoic system in South Africa, which amounted to less than 5 percent of the received coal, were discarded. (In terms of design, the UMD plant had a capture system whereas the Stoic gasifier did not.)

9. The UMD gasifier was equipped with an automatic poking system. The Stoic gasifier relied totally on manual poking.

The design modifications made by Foster Wheeler Energy Corp. were not based on actual operating experience. Hence, the UMD gasifier was not a commercially proven unit, with the design much more complex than the Stoic gasifier. Extensive repairs and modifications to the gasifier, the coal/ash handling system, and the raw gas cleanup system were required throughout the duration of the program to keep the gasifier plant operable. Three shift operators and a day supervisor were normally needed to operate the gasifier, the coal/ash handling system, and the raw gas cleanup system. As noted earlier, the labor requirements were found to be three times greater than originally anticipated.

Typical analyses of coal feed are given in Table 35. The results of 12 gasifier test runs are summarized in Table 36. The calculated test results shown allowed mass balance calculations to be accurate within 10 percent.

Carbon content was high in the residue ash: it ranged from 24.4 to 50.1 percent, for all test runs. The ungasified carbon in the ash produced a significant decrease in gasifier thermal efficiency. The high-carbon-content ash residue was the result of the mechanical design and operating speed of the rotating

grate, the operating temperatures of the fire zone, and the type of coal feed. The highest gasifier efficiency was achieved with coals containing less than 5 percent ash. However, low-ash coals were not the most desirable for UMD gasifier operation because an adequate ash bed was required on the rotating grate to prevent the grate from overheating. The coal's characteristics, especially the friability, determined the smoothness of operation. Highly friable coal, such as the Montana product, limited the rate or throughput of gasifier operation due to excessive pressure drops across the coking and drying zones.

The most difficult problem with gasifier operation was control of the fire zone level which was found to be important in maintaining a steady product gas composition and in preventing ash clinkering to the gasifier refractory wall. Melted ash stuck to therefractory wall when the fire zone spread out of control and reached a level above the water jacket. Severe ash clinkering in the refractory-lined section of the gasifier resulted in refractory damage and shutdown of the gasifier.

The UMD gasifier is similar in design to many other two-stage gasifiers that have been operated in Europe and South Africa. The test results indicate that the UMD gasifier is unique in neither efficiency nor product gas compositions.

Table 35

Typical Coal Feed Analysis for UMD Gasifier

Coal Type	Wyoming, Hot Springs	Montana, Big Horn	Colorado, Routt
Ultimate analysis (% by weight)			
Carbon	57.9	55.3	64
Hydrogen	4.2	4.0	4.6
Nitrogen	1.1	1.1	1.3
Sulfur	0.4	0.4	0.4
Oxygen	13.1	13.3	12.4
Moisture	8.6	21.5	8.9
Ash	14.7	4.4	8.4
Proximate analysis (% by weight)			
Moisture	8.60	21.48	8.87
Ash	14.72	4.45	8.4
Volatiles	33.05	30.85	34.15
Fixed carbon	43.63	48.58	
Sulfur	0.33	0.37	0.42
HHV (as rec'd) Btu/lb	10,110	9,600	11,140
Free swelling index	1	1	1
Ash softening temp. (°F)	2,350	1,940	2,260

Table 36

University of Minnesota-Duluth Gasifier Test Results

TEST NUMBER	11	8	3	9	1	10	2
COAL ORIGIN (STATE)	WYOMING	WYOMING	WYOMING	WYOMING	WYOMING	WYOMING	WYOMING
COAL FEED RATE (TONS/HR)	0.86	1.28	1.31	1.44	1.67	1.69	3.
PERCENT GASIFIER CAPACITY	29.	43.	44.	48.	56.	56.	100.
COAL HHV (AS REC. BTU/LB)	9,900.	10,110.	9,970.	10,230.	10,170.	9,650.	10,170.
BLAST STEAM (LB/LB COAL)	0.27	0.23	0.11	0.17	0.19	0.22	0.17
BLAST SATURATION TEMP. (°F)	140.	143.	138.	139.	141.	140.	136.
GASIFIER OUTPUTS							
GAS (LB/LB COAL)	3.33	2.64	2.43	2.54	2.49	2.99	2.83
TAR (LB/LB COAL)‡	0.056	0.076	0.076	0.073	0.09	0.088	0.073
CARBON IN DRY ASH (%)	42.2	34.6	47.3	34.1	50.1	36.2	38.3
GASIFIER EFFICIENCES							
COAL TO GAS (%)*	79.5	72.2	68.9	75.1	72.4	—	80.7
COAL TO TAR (%)	9.5	12.4	12.9	11.9	14.7	—	12.8
TOTAL	89.	84.6	81.8	87.	87.1	—	9.5
GAS DATA							
COMPOSTION (% BY VOL, MOISTURE AND TAR FREE)							
H2	14.9	17.9	17.9	19.6	18.9	18.2	16.8
N2-AR	52.3	45.4	45.3	44.4	44.1	44.9	46.4
CO	41.7	28.7	29.7	29.8	30.	30.6	31.8
CO2	8.6	5.4	4.5	3.8	4.3	3.6	3.1
CH4	2.1	2.4	2.4	2.2	2.5	2.2	1.7
C2H4	—	0.044	0.041	0.043	0.048	—	0.034
C2H6	0.162	0.185	0.202	0.203	0.22	0.166	0.152
C3H8	0.104	—	—	—	—	0.115	—
H2S	0.089	—	—	—	—	0.153	—
GAS DELIVERY TEMP (°F)	600.	327.	296.	266.	310.	322.	565.
H2O IN GAS (GRAINS/CLEAN SCF)**	71.5	59.7	61.1	33.9	53.9	54.5	41.
TAR IN GAS (GRAINS/CLEAN SCF)**	6.7	2.9	2.9	3.	2.9	4.2	2.9
GAS HHV AS DELIVERED (BTU/LB)‡‡	2,364.	2,768.	2,823.	3,028.	2,960.	2,966.	2,898.
BOILER 1 OPERATION DATA							
PERCENT MAXIMUM CAPACITY	32.	70.	64.	73.	88.	46.	87.
EFFICIENCY (%)	47.	75.	71.	66.	71.	66.	70.
EXCESS AIR (%)	262.	27.	45.	62.	41.	44.	35.
BOILER 2 OPERATION DATA							
PERCENT MAXIMUM CAPACITY	—	—	—	—	—	55.	86.
EFFICIENCY (%)	—	—	—	—	—	69.	70.
EXCESS AIR (%)	—	—	—	—	—	26.	31.

NOTES:
(*) EFFICIENCY BASED ON HEATING VALUE OF AS DELIVERED GAS
(**) VALUE AS GRAINS/SCF MOISTURE AND TAR FREE GAS STANDARD CONDITIONS 1 ATM, 60 °F
(‡) TAR COLLECTED IN ELECTROSTATIC PRECIPITATOR ONLY
(‡‡)GAS HIGHER HEATING VALUE INCLUDES SENSIBLE AND LATENT HEAT

Table 36 (Cont'd)

TEST NUMBER	7	4	5	6	—
COAL ORIGIN (STATE)	MONTANA	MONTANA	MONTANA	MONTANA	COLORADO
COAL FEED RATE (TONS/HR)	0.8	1.19	1.25	1.71	1.31
PERCENT GASIFIER CAPACITY	27.	40.	42.	57.	44.
COAL HHV (AS REC. BTU/LB)	9,300.	9,400.	9,480.	9,400.	10,802.
BLAST STEAM (LB/LB COAL)	0.29	0.2	0.33	0.29	0.22
BLAST SATURATION TEMP. (°F)	146.	139.	155.	152.	137.
GASIFIER OUTPUTS					
GAS (LB/LB COAL)	3.01	2.96	3.13	3.12	2.96
TAR (LB/LB COAL)(4)	0.083	0.066	0.078	0.054	0.075
CARBON IN DRY ASH (%)	40.7	32.8	38.	39.1	24.4
GASIFIER EFFICIENCES					
COAL TO GAS (%)(1)	82.6	82.1	82.9	83.7	74.9
COAL TO TAR (%)	15.8	11.3	12.	9.3	12.2
TOTAL	98.4	93.4	94.9	93.	87.1
GAS DATA					
COMPOSITION (% BY VOLUME, MOISTURE AND TAR FREE)					
H2	17.7	16.	19.2	17.7	16.8
N2-AR	46.6	47.4	46.3	47.4	45.8
CO	27.	31.	23.7	25.4	30.6
CO2	6.3	3.6	8.4	7.2	4.5
CH4	2.3	1.7	2.2	2.1	2.
C2H4	0.04	0.04	0.045	0.045	0.032
C2H6	0.165	0.135	0.149	0.152	0.192
C3H8	—	—	—	—	0.039
H2S	—	—	—	—	—
GAS DELIVERY TEMP. (°F)	292.	375.	358.	389.	374.
H2O IN GAS (GRAINS/CLEAN SCF)(2)	70.7	63.1	65.7	74.2	51.2
TAR IN GAS (GRAINS/CLEAN SCF)(2)	0.95	0.9	0.84	3.37	0.55
GAS HHV AS DELIVERED (BTU/LB)(3)	2,550.	2,609.	2,507.	2,521.	2,732.
BOILER 1 OPERATION DATA					
PERCENT MAXIMUM CAPACITY	44.	67.	65.	87.	82.
EFFICIENCY (%)	71.	73.	66.	65.	77.
EXCESS AIR (%)	35.	42.	49.	52.	27.
BOILER 2 OPERATION DATA					
PERCENT MAXIMUM CAPACITY	—	—	—	—	—
EFFICIENCY (%)	—	—	—	—	—
EXCESS AIR (%)	—	—	—	—	—

The two boilers in the heating plant that were converted to burn the gasifier product gas were originally designed and operated as coal-fired boilers. The boilers were converted to natural gas and fuel oil firing before the gasifier was installed. They had large furnace volumes to use the radiant heat from the coal bed on a moving grate. The flame from burning gasifier product gas was nonluminous and radiated much less heat than a coal bed. Table 37 lists boiler thermal efficiencies for various fuels. Assuming that the boilers could burn both gasifier gas and tar with a thermal efficiency of 75 percent, and the gasifier operates at an efficiency of 90 percent, then the overall process efficiency would be 67.5 perecent. The overall efficiency of the boiler was about 80 percent when it was operated on coal.

Environmental Assessment

Under contract to the U.S. Environmental Protection Agency (USEPA), Radian Corp., Austin, TX performed a source test and evaluation to gather data for the environmental assessment of the UMD gasification facility. Testing was conducted from February 23 to March 6, 1981, under steady-state conditions. During the test period, 280 MT of bituminous coal were gasified at an average rate of 2140 lb/hr. Samples of the major process and the discharge streams were characterized. Distribution of minor and trace elements in the product, byproduct, and discharge streams were calculated from elemental mass flow rates.

Most of the extractable organic materials leaving the gasification process was found in the electrostatic precipitator (ESP) tars and product gas streams. Less than 1 percent of the priority pollutant load in the ESP tars and the product gas was found in the combustion emissions.

The top gas contained most of the gas phase organics. The mass flow of C1 through C6 hydrocarbons in the treated top gas was about two orders of magnitude higher than in the treated bottom gas. There was no change in the gas composition of the top gas as a result of gas cleanup except for the concentration of aerosolized components. The majority of the hydrocarbons present in the combined product gas was completely combusted in the boilers. The collection efficiency of the ESP for the top gas was found to be 98 percent for tars and 72 to 74 percent for particulates, respectively. The collection efficiency of the hot cyclone for the bottom gas was not evaluated.

Water quality analyses were performed on ash-pan wastewater to determine its pollution potential should it be discharged directly into the environment. The average concentration of barium was 1.5 mg/L and that of mercury was 0.0042 mg/L. These concentrations are very near the permissible levels set in the National Interim Primary Drinking Water Standards (1.0 mg/L Ba and 0.002 mg/L Hg). The wastewater pH (12.5) was high compared with the acceptable range specified (6.5 to 8.5) in the National Secondary Drinking Water Standards (NSDWS). The total dissolved solids (1800 mg/L) was close to the NSDWS level of 500 mg/L. These comparisons with the drinking water quality standards indicate that the process wastewater will require very simple treatment (pH adjustment) or no treatment prior to discharge into surface waters.

Leaching studies were done on gasifier ash and cyclone dust to evaluate the potential for release of contaminants to the environment. Both streams could be considered nonhazardous solid wastes; none of the components found in the extracts appeared at levels greater than 10 percent of their maximum allowable concentration.

Table 37

UMD Heating Plant Boiler Efficiencies

Fuel	No. 1 Boiler		No. 2 Boiler	
	Efficiency	% Capacity	Efficiency	% Capacity
Coal*	80.3	104	81.3	102
Natural gas**	74.9	119	75.7	125
No. 2 fuel oil	79.9	128	80.5	117
Gasifier tar	71.8	46	—	—

* Boilers' 1 and 2 original performance on coal. Boilers were converted to natural gas and fuel oil firing before the gasifier was installed.

** Boilers' 1 and 2 natural gas firing capability eliminated after gasifier was installed.

Acurex Project[16]

The Acurex project involved instrumentation and data acquisition and analysis of a Wellman-Galusha coal gasification facility installed and operated by Glen-Gery Brick at its York, PA plant. Glen-Gery has been operating commercial Wellman-Galusha units for production of low-Btu fuel gas since the early 1950s. The instrumentation was designed and installed by Acurex Corp. The gasifier produced low-Btu gas from low sulfur anthracite. The hot raw gas was used directly to fire brick kilns. Operation of this instrumented gasifier from 1977 to 1979 successfully provided the process, operating, economic, and environmental data needed for commercialization of small-scale fixed-bed coal gasifiers.

Figure 40 is a simplified flow diagram of the Glen-Gery coal gasification facility. The 10-ft-diameter Wellman-Galusha gasifier is 70 ft tall. Sized coal is transported from ground level to the 50-ton storage hopper at the top of the gasifier by bucket elevator. About 1 ton/hr of coal enters the gasifier through four coal pipes. A lockhopper located between the storage hopper and the coal pipes is used to refill the coal pipes without product gas leakage. The gasifier is completely water-jacketed. Gasification air provided by a fan flows over the steaming water at the top of the jacket, where it picks up the steam necessary for gasification reactions. The air-steam mixture is introduced into the ash hopper and distributes through the grate into the bed. Ash is removed continuously from the bottom of the gasifier into the ash hopper by the revolving grate.

Raw gas leaving the gasifier at temperatures between 700 and 800 °F flows through a refractory-lined cyclone for particulate removal. The product gas, with a heating value of 120 to 150 Btu/SCF at a rate of up to 3000 SCF/min, is sent to the burners of a brick kiln.

Figure 41 is a process and instrument flow diagram of the Glen-Gery facility. Table 38 describes the instrumentation. All measurements were continuous and automated except the water flow from the gasifier jacket, ash flow from the gasifier and . ie cyclone, and laboratory analysis of coal feed and ash discharge. Data from the online instruments were initially processed by an Autodata 616 scanner. The processed data were then sent to a Modcomp II computer for further analysis. Performance of the

[16] G.V. McGurl; R.E. Maurer and D. Lonick, "Firsthand Look at Coal Gasifiers," *Instrument and Control Systems* (August 1979); G.C. Page and W.J. Rhodes, "Source Test and Evaluation Program at the Glen-Gery Coal Gasification Facility," paper presented at Miami International Conference on Alternative Energy Sources (December 1980).

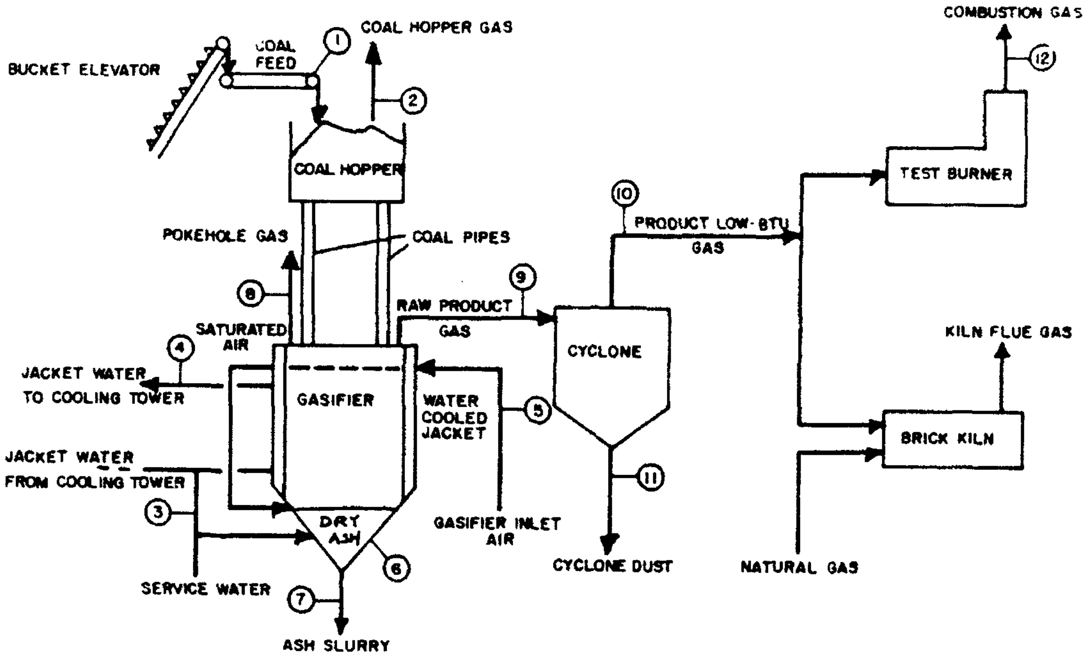

Figure 40. Simplified flow of the Glen-Gery coal gasification process.

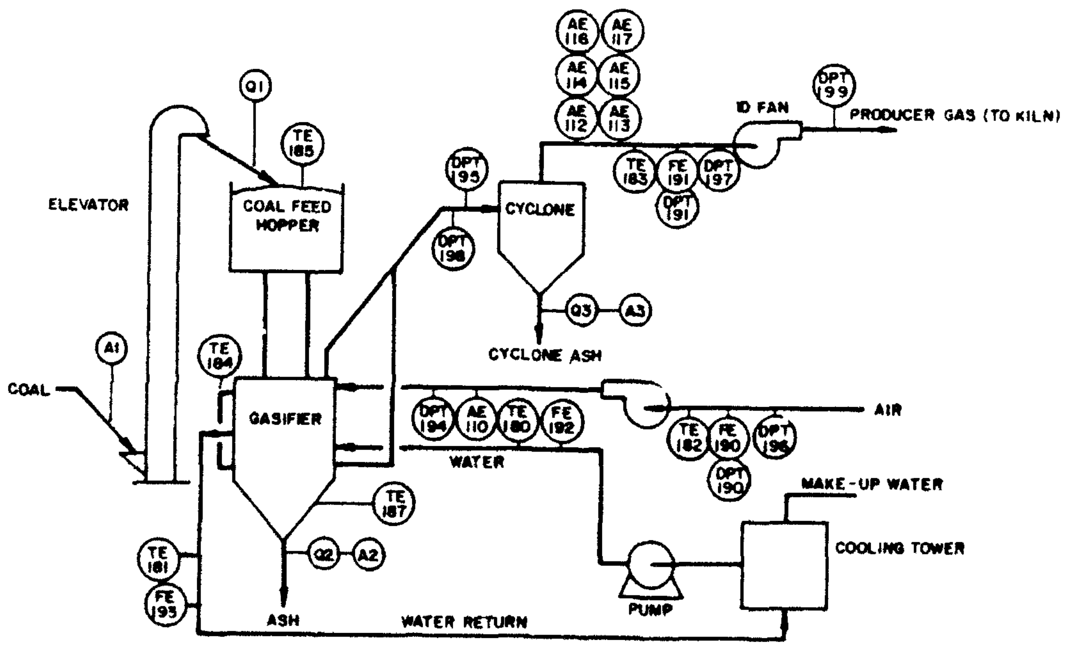

Figure 41. Simplified process and instrumentation at the Glen-Gery gasification facility.

Table 38

Description of Instrumentation Installed in Glen-Gery Coal Gasification Facility

Measurement I.D. Number	Type	Description
Q-1	Merrick	Mass of coal into gasifier
AE-110	General Eastern	Dew point of inlet air
AE-112	Hankison	Dew point of producer gas
AE-113	Teledyne 326A	O_2 in producer gas
AE-114	Herbert Sigma Ltd.	Btu content of producer gas
AE-115	Beckman	CO monitor (NDIR)
AE-116	Beckman	CO_2 analyzer (NDIR)
AE-117	Beckman	CO_4 analyzer (NDIR)
TE-180	T/C (Type K)	Inlet water temperature
TE-181	T/C (Type K)	Outlet water temperature
TE-182	T/C (Type K)	Inlet air temperature
TE-183	T/C (Type K)	Producer gas temperature
TE-184	T/C (Type K)	Inlet air saturation temp.
TE-185	T/C (Type K)	Coal bin temperature
FE-190	Dieterich-Standard Annubar	air flow into gasifier
DPT-190	Validyne P 132	Delta P across annubar
FE-191	Dieterich-Standard Annubar	Producer gas flow
DPT191	Validyne P 132	Delta P across annubar
FE-192	Hersey	Water flow into jacket
DPT-194	Validyne P 132	Air into reaction zone
DPT 195	Validyne P 132	Delta P across cyclone
DPT-196	Validyne P 132	Inlet air static pressure
DPT-197	Validyne P 132	Producer gas into blower
DPT-198	Validyne P 132	Delta P across producer outlet
DPT-199	Validyne P 132	Producer gas out of blower
AE-108	MSA 701	CO monitor
AE-109	MSA 701	CO monitor
AE-117	MSA 701	CO monitor

gasifier and its instrumentation was successful. The major conclusions and observations reached from the Acurex project are summarized as follows:

1. The cost of low-Btu gas from anthracite varied from \$2.35/MBtu to \$2.45/MBtu. This included capital, operational, maintenance, and coal costs.

2. Hot gas efficiency varied between 88 and 92 percent.

3. Raw product gas dewpoint, ranging from 80 to 100 °F, was directly related to the air saturation temperature.

4. Gas heating value increased with decreasing air saturation temperature.

5. The depth of the ash bed in the gasifier did not appreciably affect the gasifier operation, but an uneven ash bed could cause an upset.

6. Clinker formation and gas channeling in the bed, and the burning of gases at the gasifier gas outlet, also could cause operational upsets.

Under contract with USEPA, Radian Corporation of Austin, Texas conducted a Source Test and Evaluation (STE) program to gather data for the environmental assessment on the Glen-Gery facility's waste streams and fugitive emissions. Overall, the results indicate that the potential health and ecological effects of Glen-Gery's waste streams are significantly lower than those produced by gasifying bituminous coal.

Samples of 12 process and waste streams (Figure 42) were collected as well as process operating data such as stream temperatures and flow rates. This information was used to calculate the mass and major component balances around the plant and to characterize the plant's waste streams. The analyses performed for the STE program are summarized in Table 39. Table 40 shows major element balances over a 96-hr period during which the gasifier operated continuously except for a 7-hour upset due to a mechanical failure.

Figure 43 summarizes the environmental assessment results using the Multimedia Environmental Goals (MEGs) and the Source Analysis Model/Impact Analysis (SAM/IA) for the waste streams sampled. Detailed results and procedures used to evaluate the environmental data using the MEG's and SAM/IA can be found elsewhere.[17] While all sampled waste streams were found to contain constituents in potentially harmful concentrations, the total discharge severities from gasification of *anthracite* coal (Figure 43) are generally significantly less than those calculated for similar waste streams from a gasification facility using bituminous coal. That is, the anthracite produces no tar/oil which has a high environmental impact. This lower potential for harmful effects associated with Glen-Gery waste streams is also supported by the results of the bioassay screening tests.

[17] *Environmental Assessment: Source Test and Evaluation Report--Wellman-Galusha (Glen-Gery) Low-Btu Gasification*, EPA-600/7-79-185 (USEPA, 1979).

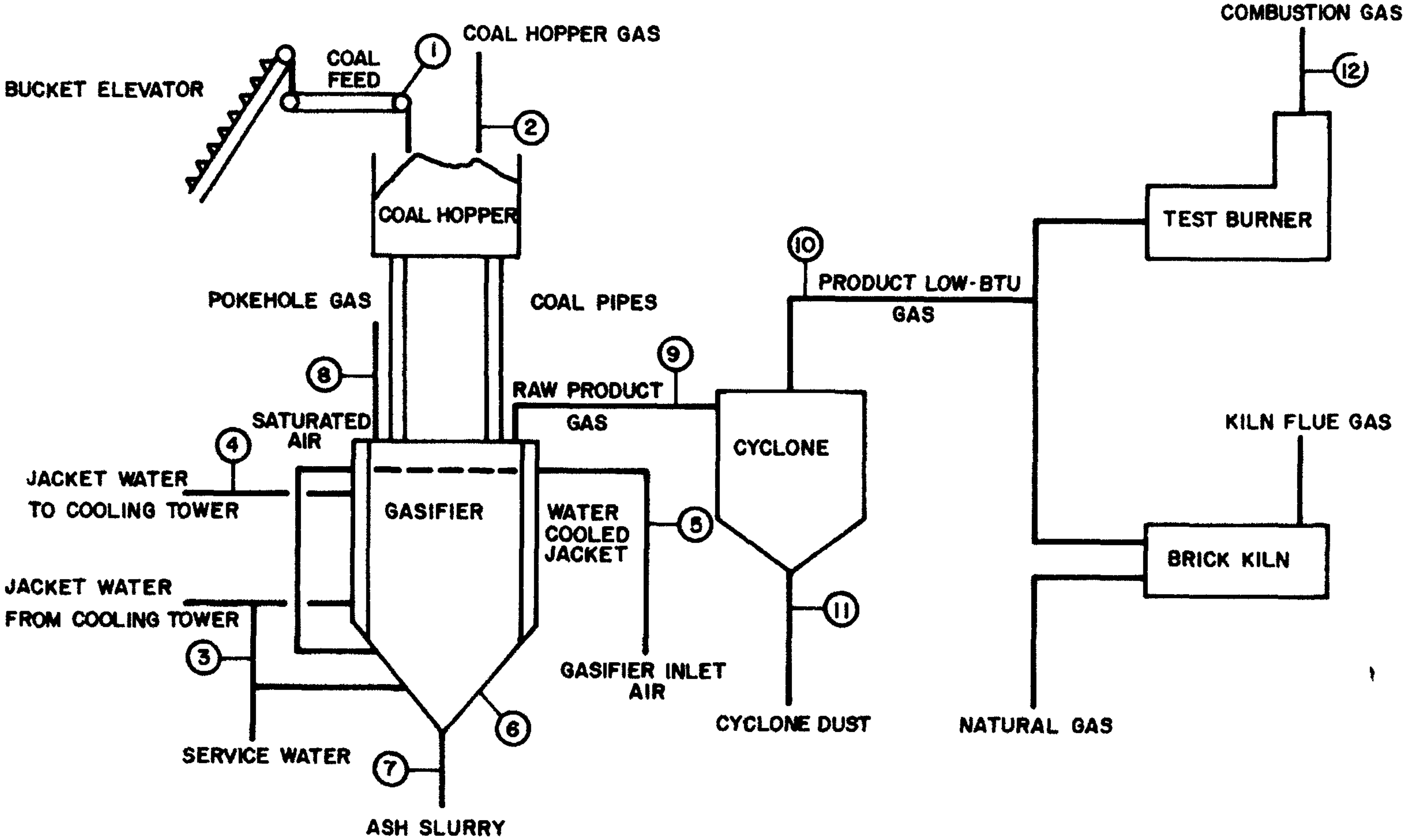

Figure 42. Process flow and sampling locations for the Glen-Gery gasifier.

Table 39

STE Program

	1	2	3	4	5	6	7	8	9	10	11	12
GASES												
Fixed gases[a]		X								X	X	
Sulfur species[b]		X								XX		X
HCN		X								X	X	
SCN^-		X								X	X	
NH_3		X								XX		X
NO_x										X	X	
$Ni(CO)_4$		X								X	X	
$Fe(CO)_5$		X								X	X	
Total Sulfur										X		
C_1–C_5 Hydrocarbons		X								XX		X
Trace elements (SSMS)[c]										X	X	
Organics (Level 1)[d]										X	X	
LIQUIDS												
pH							X			L		
TDS							X			L		
TSS							X			L		
Anions[e]						L	X			L		
NH_4^+							X					
COD							X			L		
BOD							X					
TOC							X					
Trace elements (SSMS)[c]						L	X					
Organics (Level 1)[d]			X	X		L	X			L		
Bioassay[f]						L	X			L		
SOLIDS/PARTICULATES												
Proximate/ultimate	X					X				X		
HHV	X					X				X		
Size distribution									X	X X		
Specific gravity	X					X				X		
Particle morphology	X					X				X X		
Gross and	X					X				X X		
Gravimetric									X	X X		
Trace elements (SSMS)[c]						X				X		
Organics (Level 1)[d]						X				X		
Bioassay[g]						X				X		
FLOW RATE/TEMPERATURE	X	X	X		X	X	X	X	X	X X	X	
TEMPERATURE		X		X	X				X	X X	X	

[a] Fixed Gases: H_2, CO, CO_2, CH_4, N_2, O_2.

[b] Sulfur Species: H_2S, COS, CS_2, SO_2.

[c] Trace Elements by Spark Source Mass Spectrometry (SSMS).

[d] Organics (Level 1) Ref. 1.

[e] Anions: PO_4^{-3}, Cl^-, F^-, $S^=$, NO_3^-, CN^-, SCN^-, $SO_4^=$.

[f] Bioassay Liquids: Ames, WI-38, RAM, Rodent Acute Toxicity.

[g] Bioassay Solids: Ames, WI-38, Rodent Acute Toxicity, Soil Microcosm, RAM.

L = Analysis performed on leachate.

XX = On-Line instrumentation also used.

Table 40

Major Elements for Balances for the Glen-Gery Gasification Facility

	Total Mass (kg/hr)	Ash (kg/hr)	Carbon (kg/hr)	Nitrogen (kg/hr)	Oxygen (kg/hr)	Hydrogen (Kg/hr)		Sulfur (kg/hr)
Coal	790	92	640	6.5	27	18	4.9	
Inlet Air	3,570	—	—	2,740	790	—	—	
Water Vapor in Inlet Air	700	—	—	—	620	78	—	
TOTAL IN	5,060 ± 300	92 ± 13	640 ± 90	2,750 ± 210	1,440 ± 140	96 ± 12		4.9 ± 7.0
Gasifier Ash	74	49	24	0.13	0.4	0.2	0.15	
Cyclone Dut	0.7	0.4	0.5	0.004	0.01	0.01	0.10	
Coal Hopper Gas	8	—	1.1	5	2.3	0.11	0.004	
Pokehole Gas*	6	—	1.0	4	1.7	0.11	0.006	
Product Gas	4,800	—	700	2,690	1,330	86	5.1	
TOTAL OUT	4,900 ± 530	50 ± 30	730 ± 80	2,700 ± 430	1,330 ± 110	86 ± 9	5.4 ± 1.1	

* Pokehole gas assumed to be same composition as product gas.
— Assumed to have negligible contribution to the mass balance.

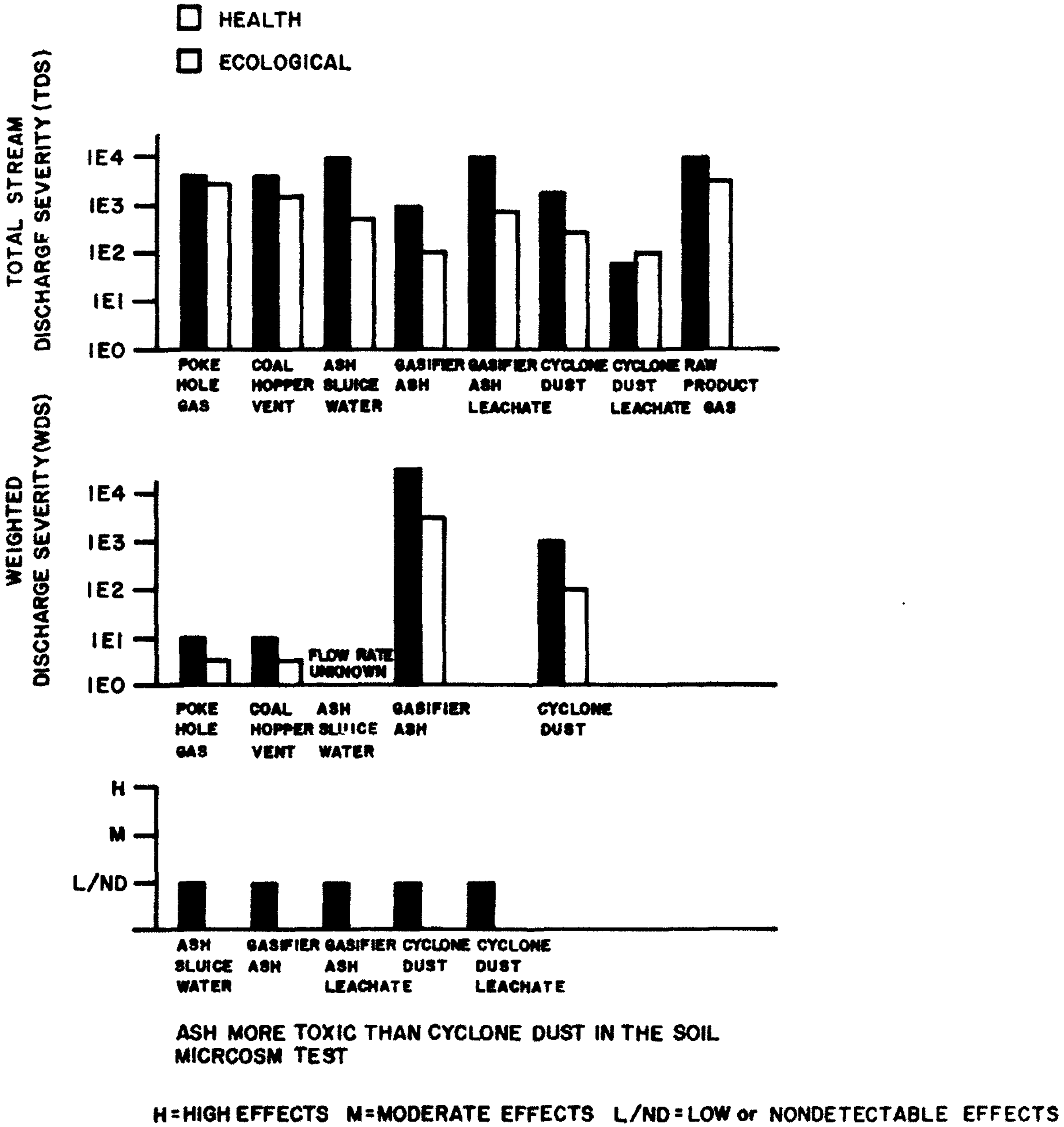

Figure 43. Total stream, weighted discharge severities, and bioassay test results for the Glen-Gery Wellman-Galusha waste streams.

5 INDUSTRIAL BOILER CONVERTIBILITY AND INTERCHANGEABILITY TO USE LOW-BTU GAS FROM A COAL GASIFICATION PROCESS

Combustion Characteristics and Performance of Low-Btu Gas vs. Natural Gas in Industrial Boiler Burners[18]

The combustion characteristics of low-Btu gas and natural gas, including flame temperature, gas volume, flame size, flame stability, and furnace efficiency were compared to evaluate the convertibility and interchangeability of existing industrial boiler burners for using low-Btu gas.

Table 41 lists typical compositions, heating values, and flame temperatures of natural gas and manufactured gases from six commercially available gasifiers. The low-Btu gases (less than 200 Btu/SCF) have lower flame temperatures than natural gas due to the large concentration of inert nitrogen. Lower flame temperatures result in lower furnace heat-transfer rates. The flame temperatures can be enhanced by air preheating and often by fuel preheating. The effect of preheating on the flame temperature is shown in Figure 44. The radiative heat-transfer rate also depends on the thermal radiation properties of the combustion products. For natural gas and low-Btu gas, the combustion products contain varying amounts of nitrogen, carbon dioxide, and water vapor. Nitrogen is transparent and radiates no heat. The individual emissivities of carbon dioxide and water vapor vary not only with the concentration (or partial pressure), but also with temperature and the radiation path length. Furthermore, the individual emissivities interact in a complex manner to affect the total emissivity. For comparison, the combustion products of natural gas and low-Btu gas, and the calculated emissivities at 3600 °F, 1 atm, and for 1 ft of radiation path, are summarized in Table 42. The combustion products of low-Btu gas radiate 10 percent less, even if the feed gas is preheated to produce a 3600 °F flame temperature.

IGT of Chicago, IL conducted a series of studies[19] to evaluate the problems of retrofitting existing burners and furnaces with manufactured gases. The performance of medium- and low-Btu gases in various industrial burners was compared with that of natural gas. The thermal radiation from the flame and from combustion products in a furnace fired with an industrial movable-vane boiler burner was measured.

Figure 45 shows the results. The furnace thermal efficiency for Wellman-Galusha air-blown fuel gas (159 Btu/SCF) and Winkler air-blown fuel gas (116 Btu/SCF) was 27.5 and 26 percent, respectively, compared with 32 percent for natural gas.

The volumes of air, fuel gas, and combustion products resulting from stoichiometric combustion of 1000 Btus of natural gas and manufactured gases are shown in Table 43. To achieve the same heat input, the low-Btu gas flow rate is about six times that for natural gas. Thus large fuel gas supply lines or higher operating pressure is required. This requirement clearly prohibits any long-distance transport of low-Btu gas. However, this problem may not be as severe for onsite gasification facilities. Less combustion air is required for low-Btu gas than for natural gas. Retrofitting thus requires no changes to the combustion air fan and duct. The combined combustion air-fuel gas volume of low-Btu gas is about 40 percent greater than that of natural gas. This will increase the pressure drop and velocity at the burner tip. The increased mixture volume promotes the internal mixing of combustion products and, hence, increases the convective heat-transfer rate. The increased flue gas volume of 28 percent for low-Btu gas would require some modifications of equipment downstream of the combustion zone to compensate for higher flow rates and pressure drops.

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[18] Gilbert/Commonwealth Co.; R.T. Waibel and E.S. Fleming, *Development of Combustion Data to Utilize Low-Btu Gases as Industrial Process Fuels*, Report No. FE-2489-48 (DOE, August 1979).

[19] R.T. Waibel and E.S. Fleming.

Table 41

Typical Properties of Clean Manufactured Gases (10 °F)

Fuel	Fuel Composition CH_4	CO	CO_2	H_2	H_2O %	N_2	C_2H_6*	C_3H_8*		Heating Value Btu/SCF	Adiabatic Flame Temperature (10% excess air), °F
Natural Gas	96.6	0.0	0.52	0.0	0.0	0.46	1.82	0.3	0.07	1020	3378
Lurgi Oxygen	9.4	18.5	29.4	40.2	1.9	0.6	—	—	—	285	3225
Winkler Oxygen	3.0	32.9	20.0	41.2	1.9	1.0	—	—	—	270	3394
Koppers-Totzek Oxygen	0.5	52.9	9.2	34.5	1.9	1.0	—	—	—	288	3573
Wellman-Galusha Oxygen	0.9	39.2	16.2	40.4	1.9	1.4	—	—	—	267	3461
Wellman-Galusha Air	2.6	26.9	7.4	14.3	1.9	46.9	—	—	—	159	2896
Winkler Air	0.6	21.4	6.9	12.7	1.9	56.5	—	—	—	116	2696

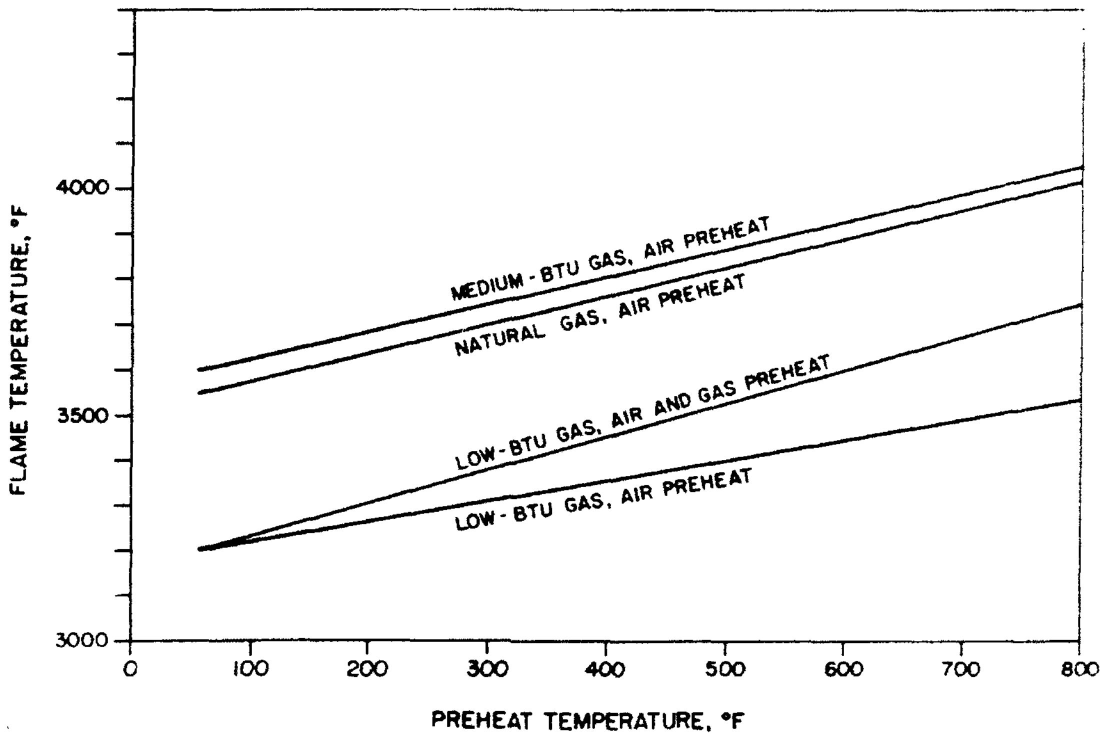

Figure 44. Flame temperature vs. feed preheat temperature.

Table 42

Comparison of Combustion Products

	Natural Gas	Med-Btu Gas (Oxygen-Blown)	Low-Btu Gas (Air-Blown)
Composition (vol %)			
CO_2	0.0952	0.2145	0.1671
H_2O	0.1898	0.1640	0.0782
N_2	0.7150	0.6215	0.7347
Emissivity (3600 °F, 1 atm, and 1-ft path)			
CO_2	0.025	0.038	0.035
H_2O	0.031	0.026	0.015
$CO_2 + H_2$	0.051	0.052	0.046
Relative radiant flux from combusted gas (Nat. Gas = 1)	1.00	1.02	0.09

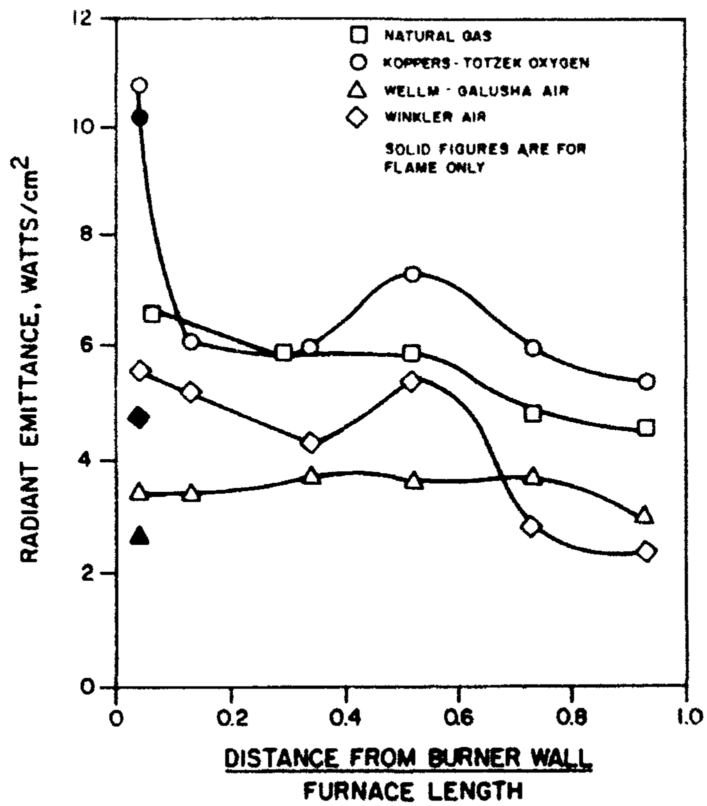

Figure 45. Thermal radiation from the flame, plus combustion products for the movable-vane boiler burner.

Table 43

Stoichiometric Combustion Properties (SCF/1000 Btu)

	Air	Fuel	Product	Air & Fuel
Natural gas	9.4	1.0	10.4	10.4
Lurgi oxygen	8.1	3.5	10.6	11.6
Winkler oxygen	7.6	3.7	10.0	11.3
Koppers-Totzek oxygen	7.4	3.5	9.4	10.9
Wellman-Galusha oxygen	6.9	3.,7	9.3	10.6
Wellman-Galusha air	7.8	6.3	12.8	14.1
Winkler air	7.5	8.6	14.7	16.1

If the modifications cannot be made, boiler derating may be necessary. The inability to handle increased flue gas volume could result in a derating up to 30 percent for low-Btu gas, depending on the type of burner and furnace. However, industrial burners, either water-tube or fire-tube, would sustain only minimal derating and require minor equipment modifications such as increasing the load on the induced and forced draft fans, or removing some of the tubes from the waste heat recovery exchanger.

The size and shape of the flame also affect the flame radiation. IGT's studies showed that low-Btu gases generally have longer flames than natural gas except inside the kiln burner, where they can be adjusted to be equal, and at the nozzle-mix burner, where they are shorter. The increased flame momentum due to increased fuel-air mixture volumes caused higher entrainment of recirculated combustion products, which diluted the air and fuel gas and increased the burnout times.

Another major concern in retrofitting an existing burner to low-Btu gas is the flame stability. Flame instability is often characterized in terms of blowoff and flashback limits. Blowoff is a condition in which the flame is pushed or "blown" out of the stability region when the stream velocity is increased above a certain limit. When this occurs, the flame is lifted away from the burner tip and extinguished. Flashback is a condition in which combustion proceeds back through the burner tip when the velocity is reduced below a certain critical value. Both conditions are a function of fuel composition, fuel-air ratio, volumetric flow rate, and burner design. IGT's studies showed that the product gas from an air-blown Wellman-Galusha gasifier has stable flames on most burners except for the flat-flame burner. The kiln and boiler burner require some fuel injector modifications to allow proper fuel flow rates at reasonable pressures.

The nitrogen oxide (NOx) emissions for cold clean low-Btu gases are much lower than for natural gas due to lower peak temperatures. The sulfur oxide (SOx) emissions are also lower, whereas carbon monoxide emissions are comparable.

Modifications Required for Retrofitting Existing Industrial Boilers

Compared with other industrial combustion equipment, industrial boilers, both fire-tube and water-tube types, require modifications for retrofit to low-Btu gases having a high heating value of 150 to 170 Btu/SCF, and would sustain minimal derating, if any. The exact modification and reduction in output would depend on the design of the individual boilers and burners.

No changes are required to the combustion air supply system. To maintain the same heat input, the volumetric flow rate of low-Btu gas is about six times that for natural gas. Therefore, the fuel gas supply system requires the most changes. For example, a larger fuel gas pipeline or a higher supply pressure is necessary to compensate for the increased volume and pressure drop. Generally, no flame stability problems are expected for low-Btu gas. However, the fuel gas nozzle/injector on certain types of burners may need to be enlarged to improve the flame stabilities.

The lower flame temperatures of low-Btu gas result in lower radiant heat transfer and lower thermal efficiency. This condition is offset, to some extent, by the higher convective heat-transfer resulting from increased volume of air and fuel gas. The overall reduction in thermal efficiency is not expected to be significant. The increased volume (about 30 percent) of combustion products can be compensated for by increasing the load on the induced or forced draft fans, and/or by removing some tubes in the waste-heat recovery unit downstream of the combustion zone.

In conclusion, the modifications and derating necessary for retrofitting the existing industrial boiler system to low-Btu gas are generally expected to be minimal. Information on the composition and combustion characteristics of low-Btu gas and manufacturing details on the boiler and burner are required to assess the exact process modifications and associated costs.

6 CONCLUSIONS AND RECOMMENDATIONS

This study has reviewed the state of the art in coal gasification technology with emphasis on small-scale, commercially available equipment and processes for producing low- and medium-Btu product gas. Units of this size range would be best suited for potential use in retrofitting gas-fired boilers at DOD installations.

The chemistry and thermodynamics of coal gasification were presented to promote an understanding of how gasifiers operate. The three types of gasifiers—fixed-bed, fluidized-bed, and entrained-bed—were explained. Coal properties such as fixed carbon content and reactivity affect the gasification reaction, and these were reviewed.

Commercial coal gasification equipment was surveyed and the findings were summarized by gasifier type. Information on coal types that can be used in the gasifiers was also presented. When available, online performance data were analyzed to determine gasifier operating efficiency for comparison to natural gas-fired plants. There appears to be a loss in boiler efficiency for the gasification process based on the equipment evaluated. However, too little data are available to make definitive conclusions about the process as a whole; for example, in the United States, the only gasifier being used commercially is the fixed-bed type.

Two experimental coal gasification projects were reviewed. One, at the University of Minnesota-Duluth, used a fixed-bed, two-stage Foster Wheeler Stoic gasifier at commercial scale. The project involved making many design modifications to the equipment not attempted previously. During its 6 years of operation, the gasifier performed near original expectations, despite continual malfunctions that were largely due to the modificatons. The other project evaluated a Wellman-Galusha coal gasification facility installed and operated by Glen-Gery Brick. Data were collected using instrumentation designed and installed by Acurex Corp. Findings indicated that this gasifier is operating successfully. An environmental assessment was also performed.

Finally, this study evaluated the potential for industrial boiler convertibility and interchangeability to use low-Btu gas from a coal gasificaton process. It appears that, for boilers at an industrial scale (as are those at DOD installations), retrofitting to use low-Btu gas from coal would involve few modifications. In addition, the system derating would be minimal, if any. Most of the changes would be to the fuel gas supply system.

Based on these findings, it is recommended that coal gasification technology be considered wherever a coal-based heating plant is required. The gasifier technologies are technically reliable and have great potential to be cost-competitive with new coal-burning plants (equipped with SO_x controls) and natural gas plants burning gas costing more than $5/MBtu.

METRIC CONVERSION FACTORS

1 Btu	=	1.055 kJ
1 SCF	=	0.028 m3
1 ton	=	907.2 kg
1 ft	=	0.305 m
1 in.	=	2.54 cm
1 psig	=	6.895 kPa
1 lb	=	0.453 kg
°F	=	(°C x 1.8) + 32

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GLOSSARY

agglomerating - a caking characteristic of coal that, in the volatile matter determination, causes the coal to give a coke residue in the form of an agglomerate button.

analysis, proximate - evaluation of a solid fuel to determine moisture, volatile matter, fixed carbon, and ash expressed as percentages of the total weight of the sample.

analysis, ultimate - chemical evaluation of solid, liquid, or gaseous fuels. In the case of coal, determination of carbon, hydrogen, sulfur, nitrogen, oxygen, and ash.

anthracite - ASTM* coal classification by rank: dry fixed carbon 92 percent or more, and less than 98 percent; and dry volatile matter 8 percent or less and more than 2 percent on a mineral-matter-free basis. Known as "hard coal."

as-fired fuel- fuel in the condition fired at the plant.

ash - incombustible solid matter in fuel.

ash bed - a layer of refuse left on the grate or deposited on a furnace floor after the fuel is burned.

ash-free basis - method of reporting fuel analysis whereby ash is deducted and other constituents are recalculated to total 100 percent.

barley - anthracite coal size—through 3/16 in. round mesh screen, over 3/32-in. round mesh screen; otherwise known as No. 3 Buckwheat.

bed moisture - moisture in coal when in the seam.

bituminous coal - ASTM coal classification by rank on a mineral-matter-free basis and with bed moisture only.

boiler - a closed pressure vessel in which a liquid, usually water, is vaporized by the application of heat.

British thermal unit (Btu) - 1/180 of the heat required to raise the temperature of 1 lb water from 32 to 212 °F at a constant atmospheric pressure. It is about equal to the amount of heat required to raise 1 lb of water 1 °F. A Btu is about 252 calories.

brown coal - lignite coal lowest in classification according to rank. Moist (bed moisture only) Btu less than 8300, unconsolidated in structure.

buckwheat - anthracite coal size:

No. 1	(buckwheat) - through 9/16 in., over 5/16 in. round mesh screen.
No. 2	(rice) - through 5/16 in., over 3/16 in. round mesh screen.
No. 3	(barley) - through 3/16 in., over 3/32 in. round mesh screen.
No. 4	through 3/32 in., over 3/64 in. round mesh screen.
No. 5	through 3/64 in. round mesh screen.

* American Society for Testing and Materials.

caking - property of certain coals to become plastic when heated and form large masses of coal.

calorie - the mean calorie is 1/100 of the heat required to raise the temperature of 1g water from 0 to 100 °C at a constant atmospheric pressure. It is about equal to the amount of heat required to raise 1 g water 1 °C. A more recent definition is: 3600/860 joules, a joule being the amount of heat produced by a watt in 1 sec.

calorific value - number of heat units liberated per unit of quantity of a fuel burned in a calorimeter under prescribed conditions.

calorimeter - apparatus for determining the calorific value of a fuel.

carbon - element; the principal combustible constituent of all fuels.

carbon loss - unliberated thermal energy lost through failure to oxidize some of the carbon in the fuel.

chain - a series of links, flexibly connected in continuous succession.

chain grate stoker - moving endless chain acting as a grate surface, onto which coal is fed directly from a hopper.

cinder - particles of partially burned fuel from which volatile gases have been driven off, which are carried from the furnace by the products of combustion.

class - rank of coal.

classification - method of separating coals with reference to their properties; - see rank.

clinker - hard, compact congealed mass of fused furnace refuse, usually slag.

clinkering - the formation of clinkers.

coal - solid hydrocarbon fuel formed by ancient decomposition of woody substances under conditions of heat and pressure.

coking - conversion by heating in the absence or near absence of air, of a carbonaceous fuel, particularly certain bituminous coals, to a concrent, firm cellular carbon product known as coke.

combustible - the heat-producing constituents of a fuel.

combustible in refuse - combustible matter in the solid refuse resulting from the incomplete combustion of fuel.

combustion - rapid chemical combination of oxygen with the combustible elements of a fuel resulting in the production of heat.

combustion chamber - see furnace.

combustion rate - amount of fuel fired per unit of time (e.g., pounds of coal per hour).

complete combustion - oxidation of all combustible constituents of a fuel.

culm - the fine refuse from anthracite production.

design load - the load for which a steam-generating unit is designed, usually considered the maximum load to be carried.

design pressure - maximum allowable working pressure permitted under the rules of the ASME* Construction Code.

distillation zone - the region of a solid fuel bed in which volatile constituents of the fuel are vaporized.

dry, ash-free basis - method of reporting fuel analysis with ash and moisture eliminated and remaining constituents recalculated to total 100 percent.

dry, mineral-matter-free basis - method of reporting fuel analysis with moisture and ash, plus other mineral matter eliminated and remaining constituents recalculated to total 100 percent.

dump grate stoker - one equipped with movable ash trays, or grates, by which the ash can be discharged at any desirable interval.

dust - particles of gas-borne solid matter larger than one micron in diameter.

economizer - heat recovery device designed to transfer heat from the products of combustion to a fluid, usually feedwater.

efficiency - ratio of output to input. The efficiency of a steam-generating unit is the ratio of the heat absorbed by water and steam to the heat in the fuel fired.

electrostatic precipitator - device for collecting dust, mist, or fume from a gas stream by placing an electrical charge on the particle and removing that particle onto a collection electrode.

excess air - air supplied for combustion in excess of that theoretically required for complete oxidation.

filter (cloth) - porous fabric that separates dust from a gas stream allowing the gas to pass through.

fineness - percentage by weight of a standard sample of pulverized material which passes through a standard screen of specified mesh when subjected to a prescribed sampling and screening procedure.

fines - sizes below a specified range.

fire box - equivalent of a furnace.

fire tube - type of boiler with straight tubes, which are surrounded by water and steam and through which the products of combustion pass.

fixed ash - that portion of the ash derived from the original vegetation, including all intimately contained minerals.

* American Society of Mechanical Engineers.

fixed carbon - carbonaceous residue less the ash remaining in the test container after the volatile matter has been driven off in making the proximate analysis of a solid fuel.

flue dust - particles of gas-borne solid matter carried in the products of combustion.

flue gas - gaseous products of combustion in the flue to the stack.

fly ash - fine particles of ash which are carried by the products of combustion.

fouling - accumulation of refuse in gas passages or on heat-absorbing surfaces which results in undesirable restrictions to the flow of gas or heat.

free ash - ash which is not included in the fixed ash.

free moisture - same as surface moisture; that portion of the moisture in coal that comes from external sources such as water seepage, rain, snow, and condensation.

friability - the tendency of coal to crumble or break into small pieces.

fuel-air mixture - proportions of fuel and air.

fuel-air ratio - the weight, or volume, of fuel vs. the volume of air.

fuel bed - layer of burning fuel on a furnace grate.

fuel bed resistance - static pressure differential across a fuel bed.

furnace - enclosed space provided for the combustion of fuel.

furnace volume - the cubical content of the furnace or combustion chamber.

fusibility - property of slag to fuse and coalesce into a homogeneous mass.

fusion - the melting of ash.

grate - surface on which fuel is supported and burned, and through which air is passed for combustion.

grate bars - those parts of the fuel-supporting surface arranged to admit air for combustion.

grindability - characteristic of coal representing its ease of pulverizing; one of the factors used in determining the capacity of a pulverizer. The index is relative; the larger values, such as 100, represent coals easy to pulverize and smaller values, such as 40, represent coals difficult to pulverize.

heat release - total quantity of thermal energy above a fixed datum introduced into a furnace by the fuel, considered to be the product of the hourly fuel rate and its high heat value, expressed in Btu per hour per cubic foot of furnace volume.

high heat value - see calorific value.

hydrocarbon - chemical compound of hydrogen and carbon.

inches water gauge (w.g.) - usual term for expressing a measurement of relatively low pressures or differentials by means of a U-tube. One inch w.g. equals 5.2 lb/sq ft or 0.036 lb/sq in.

inherent moisture - sometimes called the "bed moisture"; that so closely held by the coal substance that it does not produce wetness.

initial deformation - temperature at which a standard ash cone exhibits the first signs of rounding or bending of the apex when heated in accordance with a prescribed procedure.

lignite - consolidated coal of low classification according to rank - moist (bed moisture only) Btu less than 8300.

load - rate of output.

load factor - ratio of the average load in a given period to the maximum load carried during that period.

low heat value - high heat value minus the latent heat of vaporization of the water formed by burning the hydrogen in a fuel.

low volatile - dry fixed carbon 78 percent or more, and less than 86 percent; dry volatile matter 22 percent or less and more than 14 percent. Medium Volatile - dry fixed carbon 69 percent or more and less than 78 percent; dry volatile matter 31 percent or less and more than 22 percent. High Volatile (A) - dry fixed carbon less than 69 percent; dry volatile matter more than 31 percent - moist Btu 14,000 or more. High Volatile (B) - moist Btu 13,000 or more and less than 14,000. High Volatile (C) - moist Btu 11,000 or more and less than 13,000 (either agglomerating or nonweathering).

mechanical stoker - device consisting of a mechanically operated fuel feeding mechanism and a grate; used for feeding solid fuel into a furnace, distributing it over the grate, admitting air to the fuel for combustion, and providing a means for removal of refuse.

overfeed stoker - coal is fed onto grates by gravity before the point of air admission to the fuel bed.

underfeed stoker - stoker in which fuel is introduced through retorts at a level below the location of air distribution to the fuel bed.

micron - one millionth of a meter. The diameter of fly ash particles is usually expressed in microns.

mineral-matter-free basis - method of reporting coal analysis whereby the ash plus other constituents in the original coal are eliminated and the other constituents recalculated to total 100 percent.

moisture-and-ash-free basis - method of reporting coal analysis; see dry, ash-free basis.

multiple retort stoker - underfeed stoker consisting of two or more retorts, parallel and adjacent to each other, but separated by a line of tuyeres, and arranged so that the refuse is discharged at the ends of the retorts.

nut - anthracite coal designation through 1-5/8 in., over 15/16 in. round mesh screen. Bituminous coal size designation by some chosen screen mesh size, as 2 x 3/4 in.

nut and slack - a combination of nut and slack coal, such as 2 x 3/4 in. nut plus 3/4 in. x 0 slack (see slack).

overfire air - air for combustion admitted into the furnace at a point above the fuel bed.

oxidation - chemical combination with oxygen.

oxidizing atmosphere - surroundings that tend to promote the oxidation of immersed materials.

particle size - measure of fly ash, expressed in microns or percent passing through a standard mesh screen.

pea - anthracite or bituminous coal size; in anthracite, through 13/16 in. over 9/16 in. round mesh screen, in bituminous 3/4 in. x 3/8 in.

peak load - the maximum load carried for a stated short period of time.

pressure drop - difference in pressure between two points in a system, at least one of which is above atmospheric pressure; and caused by resistance to flow.

proximate analysis - see analysis, proximate.

pulverized duel - solid fuel reduced to a fine size.

pulverizer - machine that reduces a solid fuel to a fineness suitable for burning in suspension.

pulverizer, high speed - over 800 rpm, including impact and attrition pulverizers.

pulverizer, medium speed - between 70 and 300 rpm, including roller and ball pulverizers.

pulverizer, low speed - under 70 rpm, including ball or tube pulverizers.

rank - method of coal classification based on the degree of progressive alteration in the natural series from brown coal to meta-anthracite. Limits under classification according to rank are on a mineral-matter-free basis.

rated capacity - manufacturer's stated capacity rating for mechanical equipment, (e.g., the maximum continuous capacity in pounds of steam per hour for which a boiler is designed).

reducing atmosphere - surroundings that tend to promote the removal of oxygen from a chemical compound.

reinjection - procedure of returning collected fly ash to the furnace of a boiler for burning out its carbon content.

retort - trough or channel in an underfeed stoker, extending within the furnace, through which fuel is forced upward into the fuel bed.

rice - anthracite coal size, otherwise known as No. 2 Buckwheat—through 5/16 in. over 3/16 in. round mesh screen.

run of mine - unscreened bituminous coal as it comes from the mine.

scrubber - apparatus for removal of solids from gases by entrainment in water.

secondary air - air for combustion supplied to the furnace to supplement primary air.

semianthracite - coal classification according to rank. Dry fixed carbon 86 percent or more and less than 92 percent and dry volatile matter 14 percent or less and more than 8 percent, on a mineral-matter-free basis.

semi-bituminous - former coal classification according to rank - including Low Volatile Bituminous.

single-retort stoker - underfeed stoker using only one retort in assembly of the complete stoker. A single furnace may contain one or more single-retort stokers.

slack - rock formation sometimes overlaying or mixed with a coal seam. In connection with anthracite coal, any material which has less than 40 percent fixed carbon.

slacking - breaking down of friable coals due to changes in moisture content.

slag - molten or fused refuse.

soot - unburned particles of carbon derived from hydrocarbons.

spontaneous combustion - ignition of combustible material following slow oxidation without the application of high temperature from an external source.

stoker - see mechanical stoker.

subbituminous coal - coal classification according to rank:

A. Moist Btu 11,000 or more and less than 13,000.
B. Moist Btu 9500 or more and less than 11,000.
C. Moist Btu 8500 or more and less than 9,500.

surface moisture - that portion of the moisture in coal that comes from external sources as water seepage, rain, snow, and condensation.

tangential firing - pulverized coal burners are so located in the furnace walls that their center lines are tangential to an imaginary circle. Corner firing is usually included in this type.

tempering moisture - water added to certain coals which, as received, have insufficient moisture content for proper combustion on stokers.

total moisture - sum of inherent and surface moisture in coal.

traveling grate stoker - stoker similar to a chain grate stoker except that the grate is separate from, but is supported on and driven by, chains. Only enough chain strands are used as may be required to support and drive the grate.

ultimate analysis - see analysis, ultimate.

volatile matter - products given off by a material as gas or vapor, as determined by prescribed methods.

washed size - size of coal that has been washed.

water tube - type of boiler in which the tubes contain water and steam, the heat being applied to the outside surface.

weathering - see slacking.

zone control - regulation of air flow into individual zones of a stoker.

zone - divisions of the stoker windbox in which air can be maintained at different and controllable pressures.

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